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# Table of Contents


**AIR CONDITIONING**

What you need to know about air properties ..... 6
Cleaning air ..... 10
Heating and cooling ..... 12
Moisture control ..... 13
Air distribution ..... 17
Refrigeration ..... 17
How to fit equipment to the job ..... 20

**LUBRICANTS**

How lubricants work ..... 26
Key properties of fluid lubricants ..... 30
Additives ..... 32
Mineral Oils ..... 34
Synthetics ..... 34
Hydraulic fluids ..... 36
Greases ..... 36
Solid lubricants ..... 38

**COMPRESSING AIR**

How compressors work ..... 42
Reciprocating types ..... 44
Rotaries ..... 48
Centrifugals ..... 49
Axial-flow ..... 50
Portables ..... 51
Compressor accessories ..... 52
Controls ..... 54
Compressor selection ..... 56
System layout ..... 58
Trouble-shooting guide ..... 60

**CORROSION**

Why metals corrode ..... 62
Corrosion types ..... 66
Tools for the job ..... 68
Combatting corrosion ..... 82
Corrosion testing ..... 92
Anti-corrosion programs ..... 94

PABLO THOMASSET
INGENIERO
OBRAS ELECTROTECNICAS
RENOVACION G. TERRA

## FANS

How fans work ..... 98
Construction ..... 100
Arrangements ..... 103
Fan characteristics and performance ..... 104
Fan controls ..... 106
Applications ..... 108
Maintenance ..... 112

## PIPING

Role of Codes ..... 114
Materials for piping ..... 116
How pipe is made ..... 122
Designing the system ..... 124
Joining piping ..... 132

## PUMPS

Major classes and types ..... 139
How pumps work ..... 141
Centrifugal pumps ..... 142
Rotary pumps ..... 151
Reciprocating pumps ..... 152
Pump applications ..... 158
Pump selection ..... 164
Priming pumps ..... 167
Pumps on the job ..... 168

## REFRIGERATION

How machines make cold .....
Refrigeration machines .....
Machine components .....
System components .....
Controls .....
Refrigeration applications .....
Refrigerants and brines .....
Equipment selection and use .....

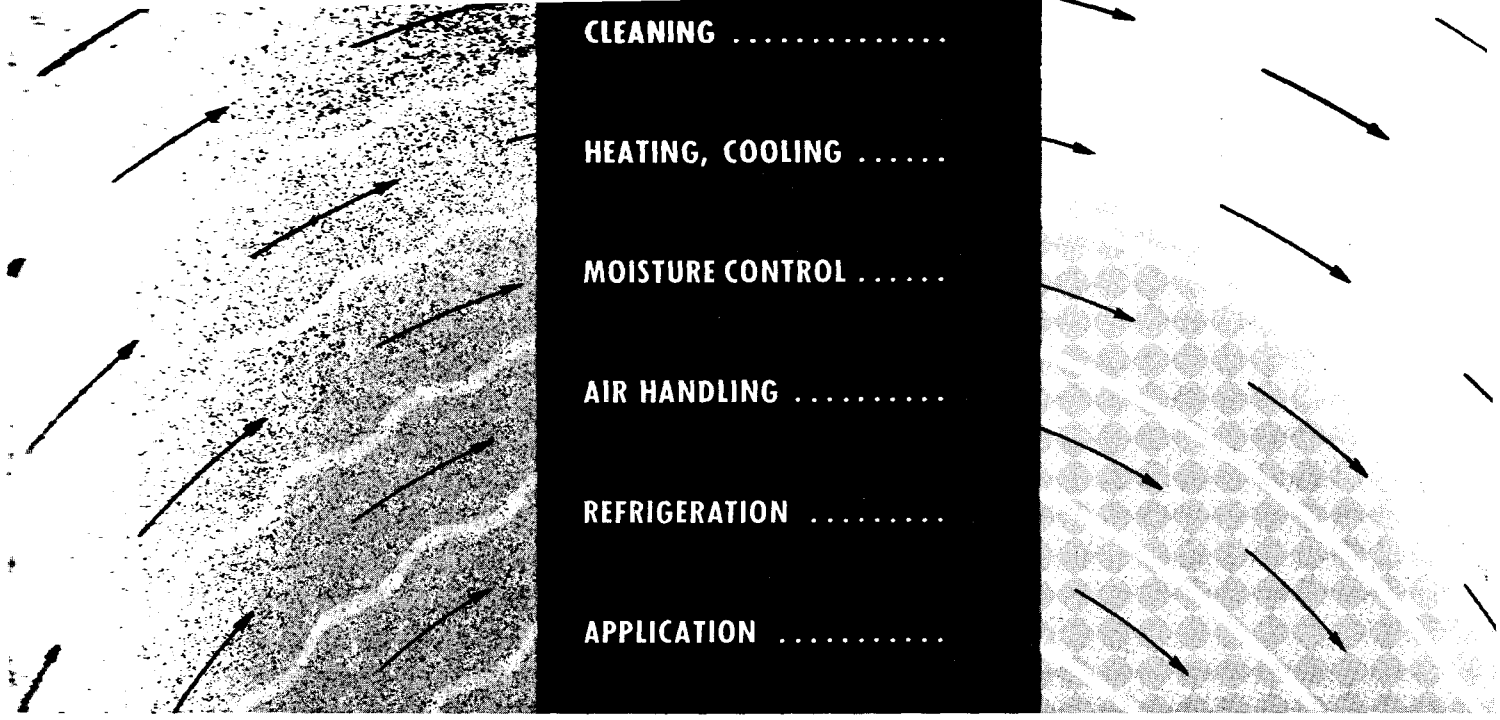
# A Word from the Editors...

This book is produced to introduce you to the kind of service you can expect from your monthly issues of POWER. We sincerely hope you find it valuable.

If you have been familiar with POWER over the years you will undoubtedly recognize the "Special Report" techniques in the eight sections of this manual. If you are not familiar with them we want to emphasize that all of them appeared originally in POWER. In fact the "Special Report" has become a POWER trademark. Every year you can expect four more similar articles in POWER to add to your growing library. In October of each year you will also receive POWER's Plant Design Issue which contains the latest thinking of engineers across the nation and surveys of new plant design trends to help you upgrade your own thinking and make sure your plant's operation is up to date.

But more important perhaps is the value crammed into *every* corner of *every* issue of POWER. We editors travel thousands of miles every year to search out the latest and best for you. There's gold in every issue if you will but take the time to look for it. From the technical articles on new design trends to the practical ideas and new equipment news there's a wealth of information here for the taking. Proper use (which means regular reading and filing) of POWER can pay off many times over in increased plant efficiency and better personal income.

We urge you to form the POWER habit—to glance at every item, including especially the advertising pages. And we also urge you to consider POWER as your property. If you have a problem or a suggestion, let us hear from you. We love compliments but we also welcome constructive criticism.




# AIR CONDITIONING

Air conditioning is an engineering service that pays for itself by (1) improving comfort (2) increasing worker efficiency (3) bettering industrial processes. It does its job by providing the ideal climate for the particular circumstances.

What makes an ideal climate depends on who wants it and why. In industrial work the specifications set up are apt to be as individual as the products manufactured. For instance, electrical insulation makers want high temperature and low relative humidity, while for some textile operations high humidity is the prime need. And so it goes.

How about comfort air conditioning? No two people are exactly alike in what they consider comfortable conditions. By extensive testing, however, certain combinations of temperature, humidity and air movement have been proved comfortable to most people. It also turns out that these factors are to some extent equivalent or interchangeable. Thus it has been possible to arrive at an index of comfort—known as *effective temperature*—which combines these three factors. Properly interpreted, this serves as a guide in setting comfort conditions.

For either industrial or comfort conditioning, means are available for altering the properties of air to those desired. This may involve cleaning, heating or cooling, humidifying or dehumidifying, and controlling distribution of air. How many of these basic operations are involved depends on the goal in mind. Comfort conditioning frequently requires all of them; industrial conditioning, as we have seen, may emphasize one or two phases.

As a major service in many plants and buildings, air conditioning represents another of the power engineer's manifold responsibilities. Much of the equipment used is familiar from heating, ventilating and refrigeration practice, while some is unique to the air-conditioning job. Most important of all, successful air conditioning depends on a knowledge of the properties of air and how they may be juggled to bring about desired results.

Thus this special section, POWER's 75th, gives a simplified presentation of first principles, plus a broad picture of the tools that put these principles to work. Emphasis naturally falls on equipment specifically developed for air conditioning, with a passing glance at familiar devices that also play a part in the job. The story is then buttoned up by showing how these elements are combined to meet the needs of any given application. The whole forms a practical primer on a power service of evergrowing importance in industrial plants, buildings and institutions.

# What You Need to Know

Behind the application of air conditioning lies an understanding of what air is and how it behaves. Pure dry air is, we know, a mixture of oxygen and nitrogen. It also contains small amounts of rare gases, such as argon, but we can forget them. Air as we find it all around us, however, contains moisture in varying amounts. Thus the stuff we deal with in conditioning can be regarded as a mixture of air and steam.

How come we get steam at atmospheric pressure and low temperatures? The answer is that while the mixture is at atmospheric pressure, the water vapor isn't. It is actually at extremely low pressure. And since we know that the temperature at which water boils or vaporizes gets lower as pressure goes down, we can see that at these extremely low pressures water will exist in the form of steam even at ordinary temperatures, say 70 F.

**Partial Pressures.** These low pressures come about because, if we mix any two gases in a given space, each acts pressure-wise as if the other didn't exist. Each is under the pressure it would have if it occupied the space by itself. Pressure of the mixture is the sum of the two *partial pressures.*

To see how this works let's start with steam at 70 F. Its absolute pressure at that temperature is 0.74 in. Hg. And 0.0011 lb of it would fill one cu ft. Now if we add enough air to make one cu ft of mixture, what do we have? Total pressure, we know, will be atmospheric pressure, say 30 in. Hg. Then the partial pressure of the air must be 30 −0.74, or 29.26 in. Hg.

**Steam Properties.** Since the water vapor or steam always acts as if there were no air present, we can get a clearer picture of how moist-air mixtures behave if we review steam properties briefly. We remember that if we heat water at some given pressure, its temperature rises. Finally, we reach a point where the water boils or vaporizes. Temperature holds steady at this point until all water has become steam. If we continue to add heat, steam temperature starts to rise and we have superheated steam.

Now if we take away heat, we lower the temperature of the steam. This goes on until we reach the temperature at which the steam vaporized. If we still cool the steam, some of it condenses. This continues, at a constant temperature and as long as we take away heat, until all the steam is condensed back to the liquid.

The important point to remember is that for any given pressure there is one temperature at which steam starts to vaporize or condense. This is known as *saturation* temperature. It depends entirely on pressure, being lower at low pressures. Furthermore, steam at any given pressure and saturation temperature has a certain density.

For convenience, let's put down some of these figures in the general range of interest:

| Temperature | Corresponding absolute pressure of saturated steam, in. Hg | Density lb/cu ft |
|---|---|---|
| [illegible] | 0.258 | 0.0004 |
| [illegible] | 0.36 | 0.0006 |
| [illegible] | 0.52 | 0.0008 |
| [illegible] | 0.74 | 0.0011 |
| [illegible] | 1.03 | 0.0016 |
| [illegible] | 1.42 | 0.0021 |

[illegible] will be found in the familiar tables [illegible]

[illegible] a cubic foot of moist air at 70 F and we find that it contains 0.0004 lb of moisture. A glance at the little table above shows that at 70 F a cubic foot will hold 0.0011 lb of steam. Since we have less, the steam must be superheated, and the table tells us how much: 70 − 40, or 30 F.

**Relative Humidity.** We can see that our cubic foot holds less moisture than it could hold. The term *relative humidity* is a measure of this. Here we have 0.0004 lb when we could have 0.0011. Ratio is 4:11, or 36%. This is the relative humidity. Notice that it is based on volume—cubic feet of moist air. The term *percentage humidity* expresses the same general idea in terms of weight. It is the weight of moisture actually mixed with one lb of dry air, compared to the weight of moisture that could be mixed with one lb of dry air at the same temperature.

**Dewpoint.** Now let's take our mixture, with 0.0004 lb of moisture in a cubic foot, and cool it down. Referring to the table again, we see that if we cool it to 40 F, it will be holding all the moisture a cubic foot can hold at that temperature. It has 100% relative humidity. Such a mixture is called *saturated.* If we try to cool this mixture further, some of the steam will condense. Temperature at which this condensation starts, in this case 40 F, is *dewpoint* temperature. As we can see, the dewpoint of any mixture of air and water vapor depends entirely on how much moisture is present. For example, a cubic foot containing 0.0006 lb of water vapor has a dewpoint of 50 F.

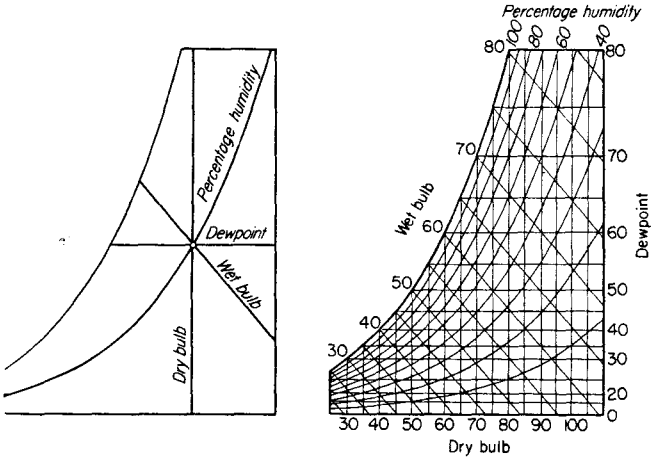
**Practical Application.** Right here we can pause for a moment and see one of the ways this knowledge of air properties can be put to work. Suppose outside air is 80 F and we find it contains 0.0011 lb of moisture per cu ft. This is about 69% relative humidity. Now let's say that we want to condition this air to 70 F and 50% relative humidity. Saturated air at 70 F would have 0.0011 lb of moisture; 50% of this would be 0.0005, disregarding the next decimal place. Looking at the table, we see that if we cooled the air down to about 45 F, moisture would condense out until only 0.0005 lb is left. Let's drain off the condensate so it can't get back into the air. Now if we reheat to 70 F, there is only a temperature change and no change in moisture content. Thus we wind up with 70-F air containing 0.0005 lb of water vapor per cu ft, which corresponds to the 50% relative humidity wanted. This little example is typical of the kind of juggling with air properties that makes air conditioning possible.

**Wet-Bulb Temperature.** We can't go around measuring the amount of moisture in each cubic foot of air we deal with. Fortunately we don't have to — with a *wet-bulb thermometer* and a *psychrometric chart* we get the answers. We make the first of these gadgets by covering the bulb of an ordinary thermometer with wetted silk gauze and placing it in a moving air stream. Some of the water in the gauze will evaporate. Since vaporizing takes heat, it will come from the remaining water and its temperature will drop. How much depends on how dry the air is and its temperature. When things settle down, the thermometer reads *wet-bulb temperature.* This, with the dry-bulb temperature read on an ordinary thermometer, tells us how much moisture is in the air and other things we want to know about it. We consult a psychrometric chart to find our answers.

**Psychrometric Chart.** Fortunately the properties of moist-air mixtures always follow the same rules, so we can figure them out once and for all and put them in the form of a chart. These can be plotted in several different ways but the basic principles are the same.

# About Air Properties

Below is a typical chart in skeleton form and, alongside it, one with some of the lines filled in. This follows the form developed by Trane Co. As the skeleton shows, the chart is a plot of percentage humidity (some charts use relative humidity), wet-bulb and dry-bulb temperature, and dewpoint. By use of auxiliary scales, as we'll see later, many additional useful data can be obtained from the chart. And for "seeing" how air properties change, the chart is valuable because we can trace on it the basic air-conditioning processes. We'll do some of this tracing later.




**1 TYPICAL PSYCHROMETRIC CHART ELEMENTS**

**Sling Psychrometer.** Since wet- and dry-bulb temperatures can be measured readily, these are usually what we start with. For convenience, we can use a *sling psychrometer.* This consists of an ordinary thermometer and one with a wetted-gauze-covered bulb, mounted on a single bracket. This has a handle so the whole outfit can be whirled around rapidly to get the air movement past the wet bulb that we need. Both temperatures can then be read at the same time.

**Latent Heat.** We've seen in passing that vaporizing water into steam requires adding heat, while condensing steam back into water requires taking heat away. It's the same amount in each case and, for the low-temperature range we're interested in, it's about 1050 Btu per lb. This is called *latent heat.*

Exact amount of latent heat varies with dewpoint. So now we can paste in our hats the twin facts that both latent heat per pound of vapor and maximum weight of vapor that can be associated with a given quantity of air depend on dewpoint alone.

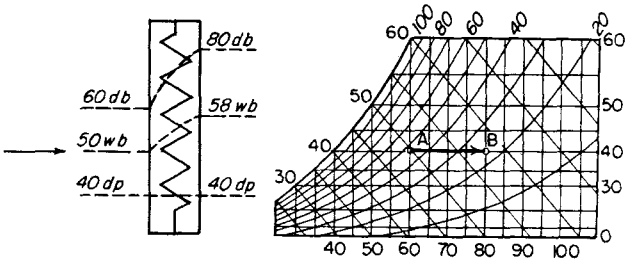
**Sensible Heat.** We've just seen that latent heat goes with a change from liquid to vapor, or from vapor to liquid. No temperature change is involved. But we know we have to add heat to raise temperature. This heat that goes to change temperature we call *sensible heat* (you can feel it). Amount of sensible heat depends on temperature and the specific heat of the substance. For dry air we can take specific heat as about 0.24 Btu per lb.

For convenience, sensible heat is measured above 0 F. So to figure sensible heat all we have to do is take the temperature and multiply it by 0.24 and we get our answer in Btu per lb.

**Total Heat.** If we had dry air alone, sensible heat would be the total heat. If we had water vapor alone its total heat would be sensible heat plus latent heat. For usual air conditions, sensible heat of moisture is extremely small, so we can neglect it. Thus total heat of moist air may be taken as sensible heat of dry air plus latent heat of vapor. For all practical purposes, it can be said to depend only on wet-bulb temperature, just as sensible heat depends on dry bulb, and latent heat on dewpoint. A reminder: dry bulb, wet bulb, and dewpoint are the same for a saturated mixture.

**What Conditions?** Before we take a look at some of the basic air-conditioning processes, let's review briefly what we're shooting at. In industrial work, the nature of the process sets the conditions we want to reach. In comfort work, we use the *effective temperature chart* — mentioned before — as a guide. To the answers it gives we must apply judgment, because comfort is affected by many factors not covered by the chart. For example, how long we're going to be in the conditioned space makes a difference, as well as the temperature outside the space. How active we are has a lot to do with it, also. And radiant-heat transmission from or to surrounding walls comes into the picture. Finally, we have to decide how much comfort we can afford to provide under a given set of circumstances.

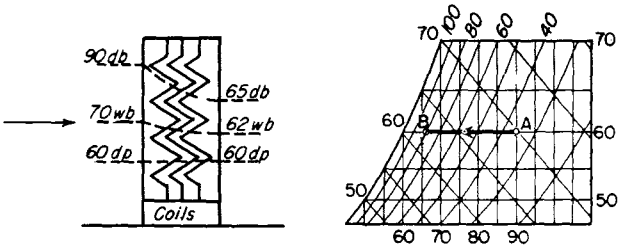
**Heating Process.** Now let's take a bit of exercise with what we've learned about air properties by tracing some common air-conditioning processes on the psychrometric chart. To save space, we just show a section of the chart in each case; if you'll turn back once in a while to the skeleton chart of Fig. 1, you'll see the whole picture.




**2 HEATING WITHOUT MOISTURE CHANGE**

Suppose we try heating first. We start with air at 60-F db (shorthand for dry bulb), 50-F wb and about 40-F dp. Pass this through a standard heating coil and what happens? Fig. 2 shows the changes diagrammatically and on the psychrometric chart. Since we haven't added or taken away any moisture, dewpoint doesn't change. And that means that latent heat won't change. We do increase the air's sensible heat and dry-bulb temperature goes up. Total heat goes up also, and so does the wet-bulb. Line *A-B* on the chart shows the change, as we move along a line of constant dewpoint. For this case, we wind up with 80-F db and about 58-F wb.

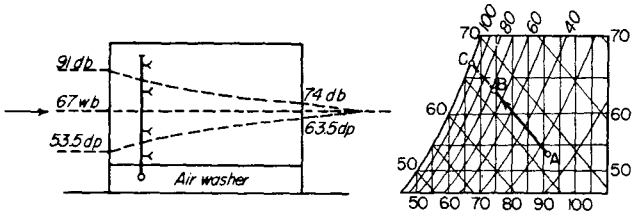
**Cooling Process.** As you might expect, cooling is the reverse, as long as we don't cool enough to cause some condensation. Let's start with 90-F db, 70-F wb and 60-F dp (point *A*, Fig. 3). Let's cool down to 80-F db, point *B*. The wet bulb turns out to be 61 F and the dewpoint, of course, stays at 60 F. Why, of course! If no moisture




## 3 COOLING WITHOUT MOISTURE CHANGE

condenses out, the only change has been sensible cooling and dewpoint isn't affected.

**Spray Humidifying.** One way of adding moisture to air, *or humidifying,* is by passing it through water sprays. This is done in *air washers,* typical examples of which are shown on pp 83-85. Suppose we start with air at 91-F db, 67-F wb and 53-F dp, and water, at 67 F. Let's further suppose that we recirculate the water, without either heating or cooling it. Being at the same temperature as the air wet-bulb, water temperature will not change. It can neither add nor remove heat from the air. Yet if we are to have evaporation, we must have a heat transfer. What happens is that the air's sensible heat changes into latent heat. This supplies the heat needed for vaporizing some of the water. In the process, the air dry-bulb goes down. Total heat of the air does not change, merely the proportions of sensible and latent heat.



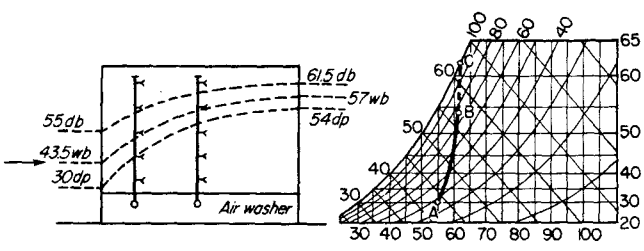

## 4 COOLING AND HUMIDIFICATION SPRAYS

Because the moisture content of the air changes, the dewpoint rises. If there were time enough for the process to go to completion, and everything went perfectly, air would leave the washer saturated at the wet-bulb temperature. Thus the dry-bulb would drop to the wet-bulb, and the dewpoint would rise to it. Since no washer is perfect, these results are only approached in practice. What we have accomplished is cooling (dry-bulb is reduced) and humidification (moisture content increased).

Suppose the water temperature hadn't been the same as the air's wet-bulb? If it were recirculated without heating or cooling, it would soon reach the air's wet-bulb temperature and would then stay there.

**Heating, Humidifying.** In winter, we might want to heat the air as well as humidify it. To do this, we've got to have water at a temperature above the air's dry-bulb. We've also got to add heat to it continuously to keep the water from assuming the air's wet-bulb temperature. We've just seen that this is what it would do if we just recirculated it. Fig. 5 shows what happens.

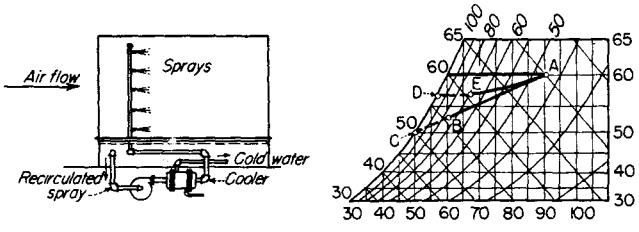
Air enters at 55-F db, 43.5-F wb and 30-F dp. (point *A* on the chart). Condition of the leaving air is shown at point *B*: 61.5-F db, 57-F wb and 54-F dp. We can see that this is not merely a shift of sensible and latent heats, as before. Wet-bulb has gone up, so total heat has gone up, too. Heat




## 5 HEATING AND HUMIDIFICATION SPRAYS

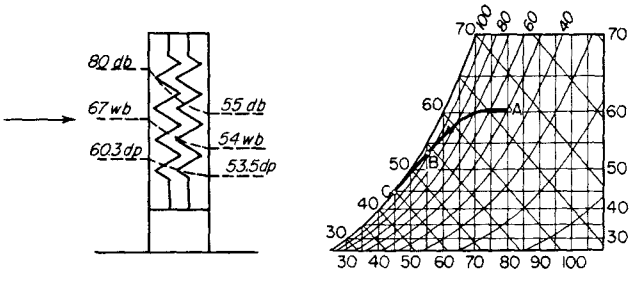
added to the air to bring about this total heat change came from the spray water and that's why we arranged to heat the spray water rather than merely recirculate it.

**Cooling, Dehumidification.** Taking moisture out of air by passing it through water sprays sounds queer, but it works. The trick lies in keeping the water temperature below the air's dewpoint. Fig. 6 shows what happens. This time we put a cooler in the washer-water circuit to take away heat and hold temperature of the water below the air's dewpoint. Air gives up enough heat to the water to drop its temperature below the dewpoint and some of its moisture condenses out. Line *AB* shows what would happen if water temperature could be held constant, with point *C* being the final water temperature. If spray-water temperature rises while it is in contact with the air, and it will, line *AD* represents a more practical case. As long as final temperature of the spray water is held below the air's initial dewpoint, both cooling and dehumidification will occur.




## 6 COOLING AND DEHUMIDIFICATION SPRAYS

**Dehumidifying With Coils.** Cooling and dehumidifying can be done with coils as well as with water sprays. Again the trick lies in keeping the coil temperature below the air's initial dewpoint. Fig. 7 shows the process. We start with air at 80-F db, 67-F wb, and 60.3-F dp. The cooling coils pull these figures down to 55-F db, 54-F wb and 53.5 dp. You



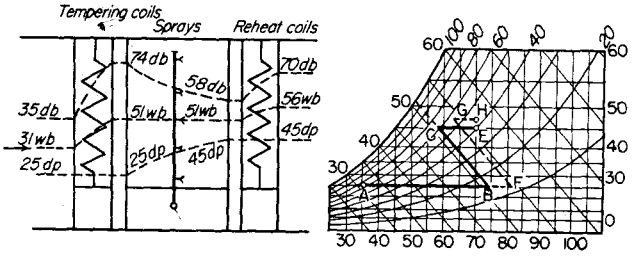

## 7 COOLING AND DEHUMIDIFICATION COILS

may wonder why the line for this process, *AB,* differs in

shape from the line *AD* for washer dehumidification, Fig. 6. Here's the reason: with sprays, water temperature rises during the process, while with coils, temperature of the air film in contact with the coils, which sets airstream conditions, goes down as successive coil rows are passed. Where point *B* falls depends on coil design.

**Coils and Sprays.** Some installations do heating and humidifying in separate steps, Fig. 8. Ahead of the washer we have *tempering coils* and after it we have *reheating coils*. Washer spray water is recirculated without heating or cooling.

Air enters the tempering coils at point *A* on the chart. In the coils, it gains sensible heat without change of dewpoint. In the washer, it is cooled along a line of constant wet-bulb, with no change in total heat; some of its sensible heat is converted to latent heat. We come out of the washer with air that is nearly saturated and at a dry-bulb temperature that is lower than desired, even though it is higher than the entering air. We then use the reheating coils to pull the dry-bulb to the desired level and correct the humidity to a proper level. We can see that for any given set of outside conditions and desired inside conditions, we can adjust the amount of heating in the two sets of coils accordingly.




## 8 HEATING BY COILS, HUMIDIFYING SPRAYS

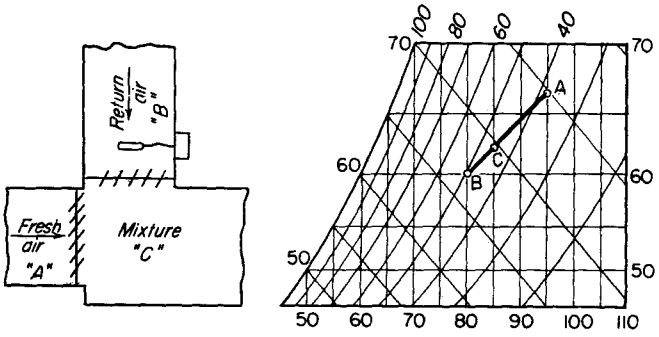
Process on the psychrometric chart runs from *A* to *B* to *C* to *E*. Final dewpoint is really set by tempering coils. For example, if we raised temperature of the entering air further, to point *F*, temperature of the spray water will rise to meet the new wet-bulb. This changes the air condition leaving the washer to point *G*, a higher dewpoint. We then reheat to H, which gives the same final dry-bulb as before, but with a higher wet-bulb and higher relative humidity.

**Chemical Dehumidification.** Certain materials, called *sorbents*, are used to take moisture out of air. (see pp 85-87 for data on materials and methods). Latent heat released by the condensing moisture adds to the air's sensible heat and raises its dry-bulb temperature. We might expect this heat gain to be balanced by the latent-heat loss, with total heat and wet-bulb staying the same. It doesn't — here's why:

Whatever sorbent is used, there's a certain *heat of absorption* associated with the process. Temperature of the sorbent goes up and so does that of the air in contact with it. The air experiences both a sensible and latent heat gain from this source. Where final temperature as well as humidity is important, it is customary to follow up the dehumidifier with a cooling coil. This brings final temperature down along a constant dewpoint line.

**Air Mixtures.** In many air-conditioning systems, air returning from the conditioned space is mixed with incoming fresh air. It is thus important to know what happens when such a mixture takes place, and what the resulting condition is.

In the simplest case, Fig. 9, the conditions of one air are shown at point *A*, the other at *B*. Somewhere along a line drawn between them, at point *C* for example, we find the conditions of the mixture. Where point *C* falls depends on the percentage of each air in the mixture. If the mixture is a 50-50 one, point *C* will fall halfway between *A* and *B*. If the mix is ⅓ air *A* and ⅔ air *B*, point C will fall ⅓ of the way from *A* to *B*. This is what you would expect — it is natural that the conditions of the mixture would reflect the conditions of the largest component of it.




## 9 MIXING AIR AT DIFFERENT CONDITIONS

**Sensible-Heat Factor.** In practical air-conditioning work, the designer's problem is to select the supply air conditions that give the desired results in the conditioned space. Each such space presents a heat load of some kind — people, machines, lights, solar heat on walls, etc. Supply air must be able to pick up the load and still produce the conditions wanted.

Effect of picking up such loads is a gain in total heat of the supply air. Depending on the nature of the loads, this may come in the form of sensible-heat gain, latent-heat gain, or some combination of them. Ratio between the sensible heat and the latent heat gain is thus extremely important.

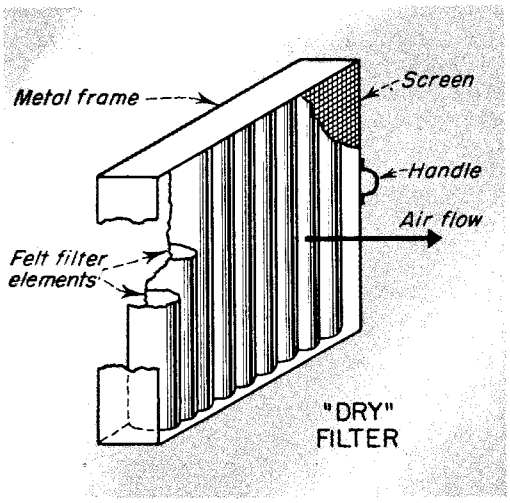
**How It Works.** To see why this is so, let's assume that we're delivering air to a conditioned space and that this air has, as a result of the conditioning method used, a relatively high moisture content. If the heat gain in the conditioned space is all sensible heat, we will probably wind up all right. Result of the heat gain will be a higher dry-bulb and lower relative humidity.

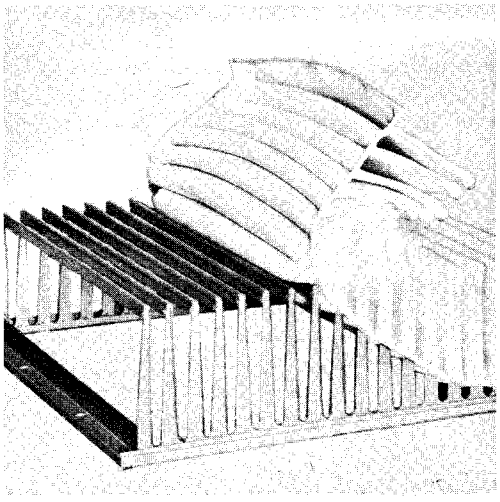
But let's assume it's the other way around, and we have a high latent heat gain. We'll wind up with room air that is saturated, or nearly so. It will certainly be uncomfortably humid. The answer, of course, lies in reheating the supply air before it reaches the conditioned space. This gives us a sensible-heat gain, pulls down the relative humidity, and puts the supply air in shape to handle the latent heat load of the space to be conditioned.

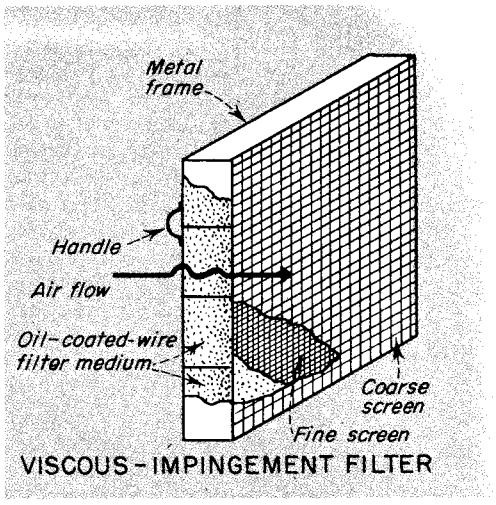
**Figuring Heat Gains.** Handbooks give the information needed to estimate sensible- and latent-heat gains. When these are known, the procedure followed to arrive at desirable supply-air conditions depends largely on which type of psychrometric chart is used for calculations. Without going into detail, most of these methods result in locating on the chart a *condition line*. Each point on this line represents a combination of dry- and wet-bulb temperatures for the supply air that meet the given heat-gain conditions. Important point is to select a combination that matches what the air-conditioning equipment is able to do. If the equipment selected cannot meet the supply-air conditions necessary, it must be modified, perhaps by addition of a reheating coil, or by some other change.

In the foregoing, we've hit the high spots of air properties and how they can be changed. Following pages show equipment available for the job, and how these devices are combined into working systems to meet the needs of various types of installations.

## VARIOUS FILTER MEDIUMS SERVE JOB NEEDS, INCLUDE "DRY" UNITS...



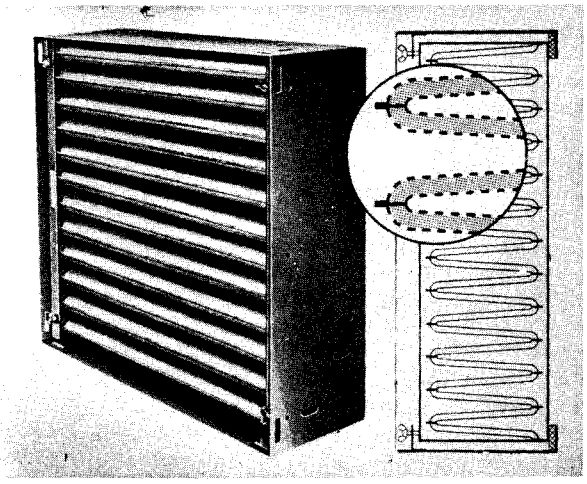



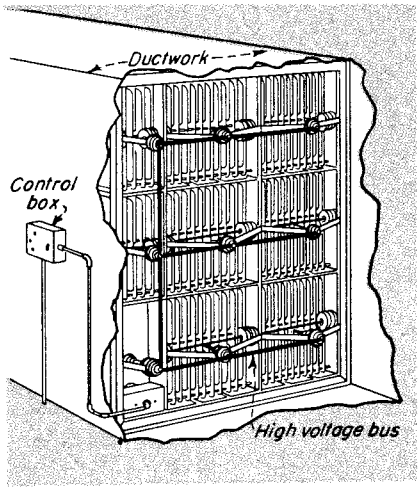


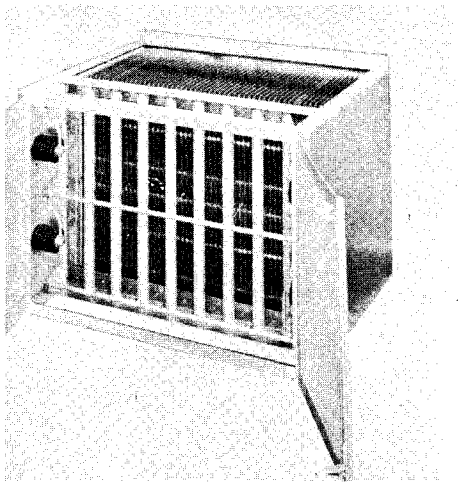

**1** "Dry" filters act like fine-mesh screen to sift dust particles from air stream. Wool felt forms a common filtering medium; shown above is a design for easy cleaning

**2** In viscous filters air passes oily fibers, dust is caught on the sticky surfaces

## THESE CLEANING DEVICES HANDLE EXTREMELY FINE PARTICLES, ODORS





**5** Objectionable odors and vapors can be removed by activated-carbon units placed in ductwork

**6** Electrostatic precipitators remove extremely fine dust particles, pollen, and smoke. Viscous material on plates holds collected particles

# Here Are the Tools . . .

To condition air completely, as we have seen, we must remove dust and other foreign matter, regulate temperature, control moisture content, and distribute air as needed. To this 4-part job we usually add another step—providing basic sources of heat (a boiler, for example) and of cold (refrigeration machinery). For these five phases of the over-all job we have a considerable variety of equipment — some familiar from heating and ventilating practice, some specifically developed for air-conditioning work. In the following pages, we'll take a look at typical examples of this equipment, passing lightly over the familiar devices and lingering longer on the specialized units applicable to this field.

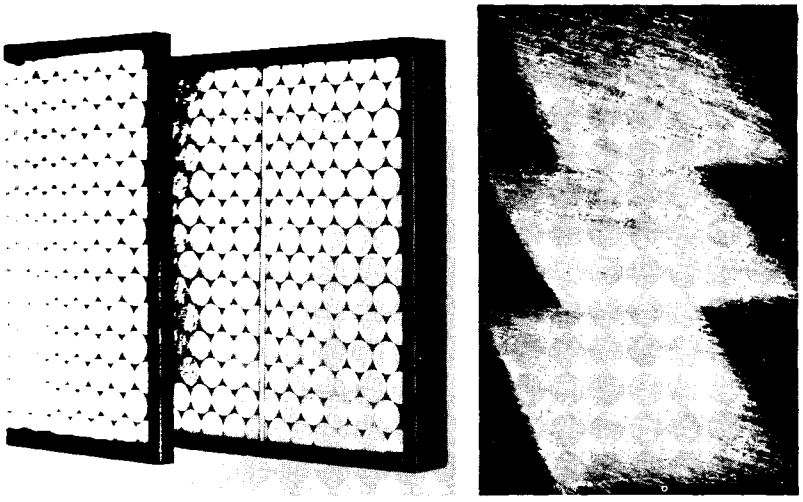
## Cleaning

Virtually all air-conditioning systems bring in some fresh air to replace air allowed to leak out of the conditioned space. This outside air brings with it dust, pollen and other foreign matter. Furthermore, air that is recirculated may pick up dust, cigarette smoke, odors, etc. Thus our cleaning job may include both fresh and recirculated air, and removal of more or less tangible particles, such as dust, or microscopic particles of smoke or vapors. To some extent, then, the equipment used, and where it is placed in the system, depends on how much of this cleaning job we elect to do.

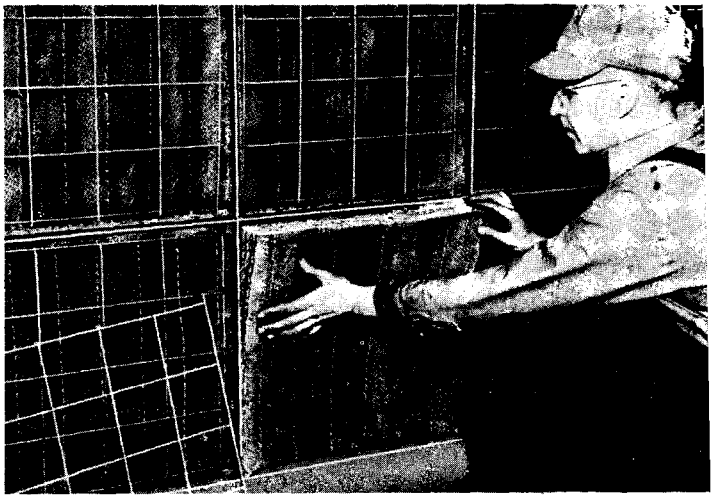
Devices that screen out particles by mechanical means are usually called *filters*. The ideal filter would (1) take out *all* dust particles (100% efficiency) (2) offer no resistance to air flow, and (3) need no maintenance. Selecting a filter for any given job involves balancing these several factors to best fit the particular conditions.

Filters may be divided into two broad classes: (1) *throwaway* units in which the filtering medium is made cheaply enough to be disposed of when

## AND RECHARGEABLE CELLS USING VISCOUS-IMPINGEMENT PRINCIPLE



**3** Filter medium for viscous units may be glass fiber, wire, crimped metal, packed closely and coated with sticky oil



**4** When a cell becomes dirty it is taken out of the bank, replaced with a spare. It can then be cleaned and recharged

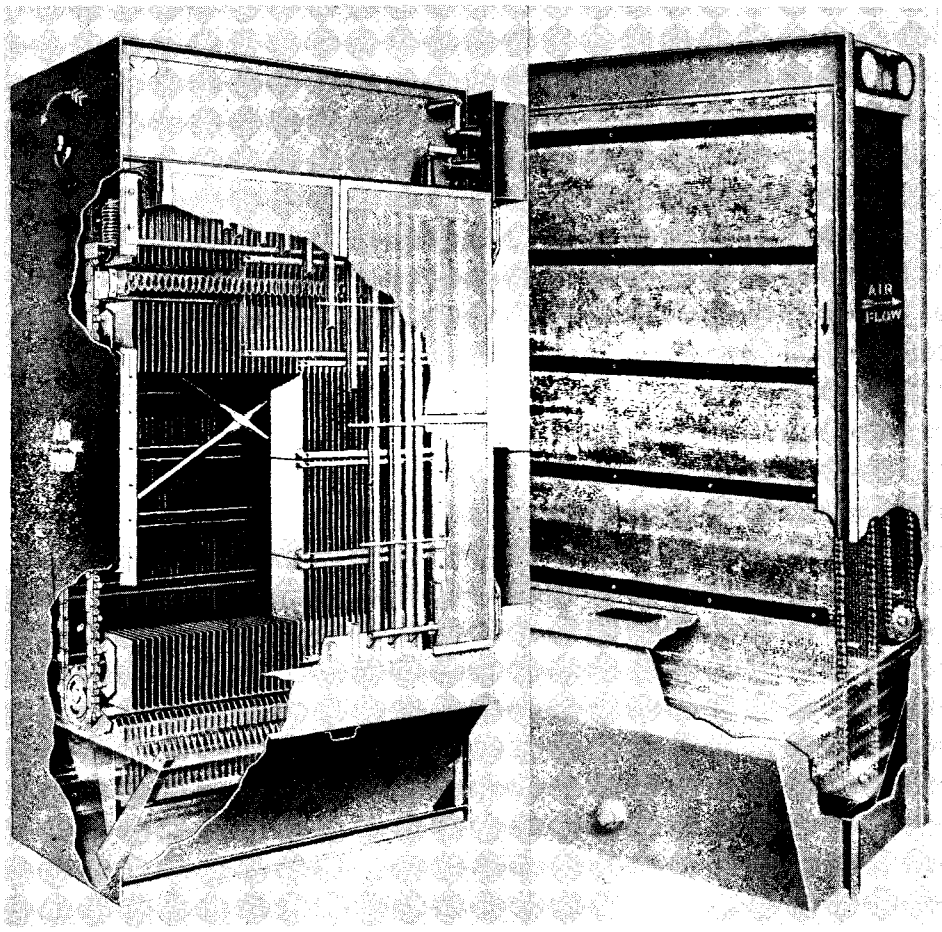
it is dust laden, and (2) *cleanable* types, which can be reused.

**Dry Filters.** Filters may also be classified by the principle they operate on. So-called *dry* filters "strain out" dust particles by forcing air to flow through a screening material, such as tightly woven wool felt, gauze, cellulose, etc. For throwaway use, filtering medium is cheap and the frame or holder is cardboard or other inexpensive construction. Type illustrated in Fig. 1 is cleanable. It uses wool felt, arranged on a metal frame to make maximum surface available in small space. Such units can be vacuum cleaned, air blown, or dry cleaned.

As a class, dry filters serve best for relatively small air flows and light dust loadings. They are highly efficient and, when clean, offer relatively little resistance to air flow. Resistance builds up rapidly, however, and dust-holding capacity is relatively small. Change in resistance usually indicates when filter should be replaced or cleaned.

**Viscous Filters.** In these units, air flows between tightly packed fibers or surfaces (glass wool, wire, crimped metal, etc.) which are coated with a sticky oil. Dust particles impinge on the viscous surfaces and are held. In most designs, filtering material is packed tighter in the direction of air flow, so air passages become progressively smaller, Fig. 2. With light, cheap frames, viscous filters may be used and thrown away. With more permanent constructions they are designed for cleaning and re-use. A typical installation consists of a bank of individual filters or "cells", Fig. 4. Cells may be removed from the bank one at a time and replaced with a spare. Dust-laden filter elements may then be cleaned and recharged with oil for further service.

## CONTINUOUS SELF-WASHING FILTER DESIGNS

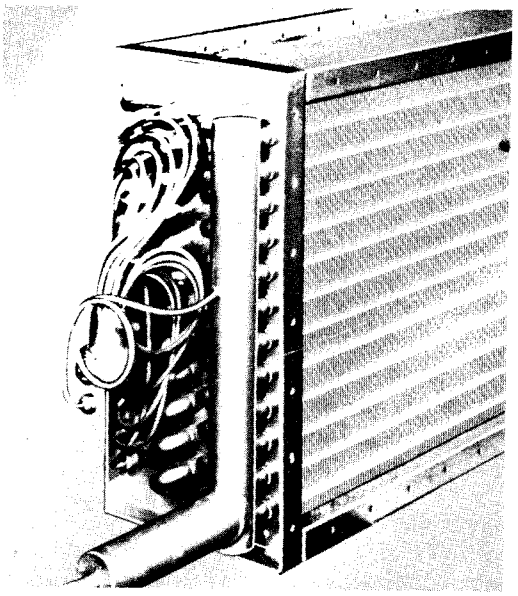



**7** By moving filter elements through an oil bath they are continuously cleaned and recharged. Unit, *right*, uses viscous-impingement principle; *left*, electrostatic

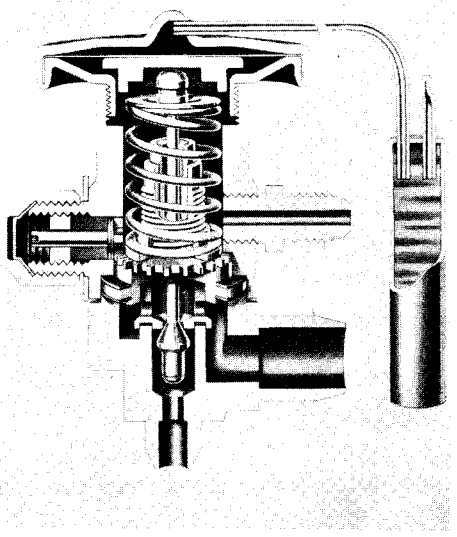
Initial resistance of viscous filters runs slightly higher than for dry filters, but rises more slowly in service. Dust-holding capacity is greater.

**Self-Cleaning Filters.** The viscous principle is often employed in filters that clean and recharge themselves continuously, Fig. 7. Filter elements, which may be like those in stationary units, Fig. 4, or may be perforated metal plates, are mounted on endless chain that moves intermittently. The

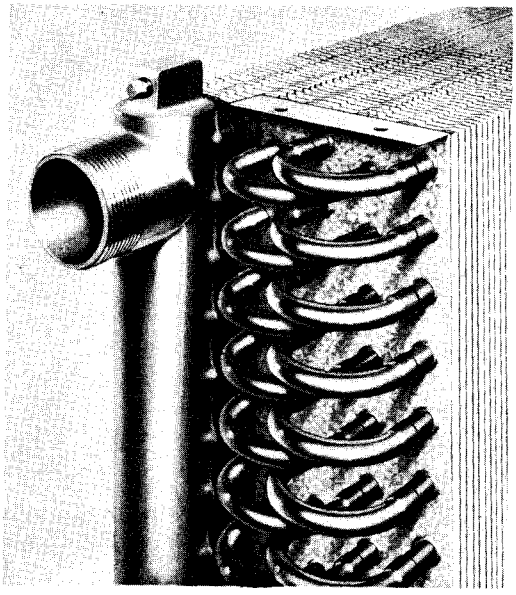
## COOLING AND HEATING COILS MAY CARRY REFRIGERANT, WATER, OR...



**8** Vaporizing refrigerant in direct-expansion coil abstracts heat from air



**9** Thermal expansion valve controls the refrigerant's evaporation in the coil



**10** This coil carries chilled water, a cooling medium used in many jobs

elements pass through an oil bath at the bottom of the unit. This cleans and recharges them. Such units offer a relatively constant resistance to air flow and require little maintenance except occasional scraping of sludge from the oil bath. Since cost of motor drive and control doesn't decrease proportionately as size of unit goes down, these designs usually prove economical on larger installations.

**Electrostatics.** Devices of Fig. 6 make use of the fact that a dust particle exposed to an electrical field assumes a charge and migrates to one of the electrodes. Pre-ionizing wires set up a high-tension field (around 12,000 v) through which air flows. Precipitation takes place in a lower-voltage secondary field of positive and negative plates set parallel to flow.

Usual design has plates coated with a viscous material to hold the attracted particles. When cleaning is needed, the unit is shut down, washed with water sprays and recoated. Electrostatic units are also built self-cleaning, Fig. 7.

Electrostatic precipitators are highly efficient on extremely fine materials and remove smoke and other microscopic particles beyond the reach of mechanical filters.

**Odor Removal.** Odors and objectionable vapors can be removed in several ways, adsorption being relatively common. Tubes or canisters filled with activated carbon are mounted in the ductwork with a filter ahead, Fig. 5. When the carbon has adsorbed up to about 20% of its own weight it must be reactivated.

Dusts, water-soluble gases and vapors may be removed by washing or scrubbing the air. *Air washers* serve as triple-threat units, being used also to control temperature and humidity. We'll take a look at them a little further along. Air *scrubbers,* as distinguished from washers, may be employed where it is desirable to reclaim dusts from air (industrial exhaust systems, for example). They consist of plate surfaces set in zigzag fashion with a water film running over them. Air must pass through narrow openings between scrubber surfaces. Solids left behind on them carry down to a settling basin out of the air stream. Such scrubbers also remove some gases and vapors.

# Heating, Cooling

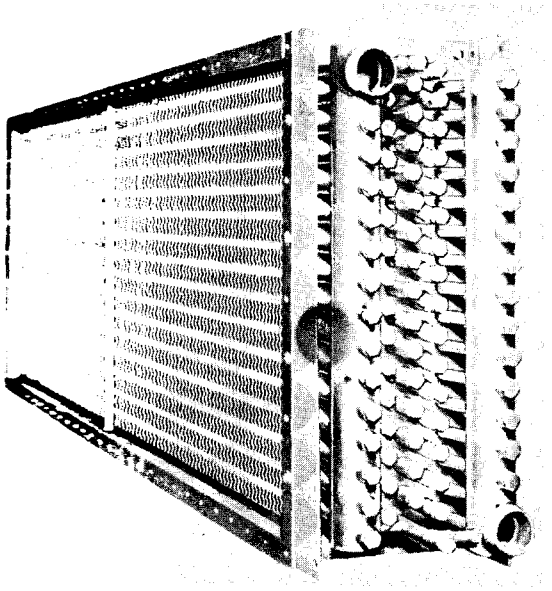
Temperature control in a summer air-conditioning system involves cooling, of course, and usually some "reheating." In year-round systems, the heating function becomes equally important. Cooling medium may be chilled water, brine or refrigerant; heating medium may be steam, hot water, or, occasionally, refrigerant vapor. Heat transfer to and from the air stream may be *indirect,* by coils, or *direct,* by sprays, Fig. 12, or combinations. Spray scheme usually means an air washer, the triple-threat device mentioned before. Because it buttons up three jobs, we'll discuss it later.

Here we're concerned with coils, which make possible a closed and balanced heating or cooling circuit. Since there is no contact between the heating or cooling medium and the air stream, we have freedom of choice and can, under some conditions, use refrigerant liquids and gases for the job. Coils used purely for heating resemble closely those described in "Building Heating," POWER, June 1949, pp 81, 82. Let's take a look at coils for cooling.

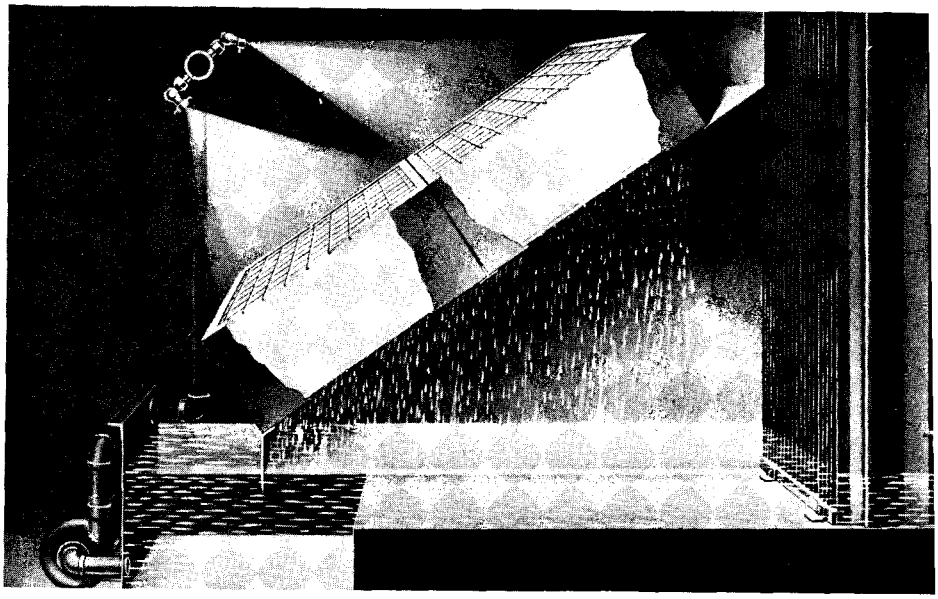
**Direct Expansion.** As permitted by local codes, certain refrigerants (Group I, American Standards Assn) can be used directly in the cooling job. In such *direct-expansion* coils, liquid refrigerant vaporizes and in so doing extracts heat from the passing air stream. This forms a simple and economical arrangement, particularly in smaller systems. Bear in mind, however, that these coils handle a volatile refrigerant, and so certain precautions must be observed. Coil should be uniformly and effectively cooled throughout, and the compressor protected from entrained unevaporated refrigerant.

There are two basic control methods for direct-expansion coils. The *flooded* coil (not widely used in air conditioning) has a small surge tank. A float keeps liquid refrigerant at desired level in both coil and surge tank. *Thermal-expansion* valves, Fig. 9, are commonly used. Such a valve feeds just enough liquid to the coil to hold refrigerant at coil's suction outlet at about 6-10 F superheat. This is measured by a temperature bulb, which actuates the valve. It is usual practice to get this superheat within the coil so coil length is selected with this in mind. Every effort is made to hold pressure drop in the refrigerant circuit at practical levels. This may require more than one refrigerant feed per expansion valve. When several feeds are used, a dis-

## STEAM; WATER SPRAYS MAY ALSO BE USED FOR THE COOLING JOB



**11** Where solids in water may plug coil, user may want clean-out type



**12** A spray of cold water played across the path of the air stream can be used to cool it down; in addition it sets dewpoint for control of the air's humidity

tributor divides refrigerant equally between feeders.

**Chilled Water.** More common practice, particularly in larger installations, involves indirect cooling by means of chilled water. Refrigerant expansion and consequent cooling is done at a central point, and actual cooling of the air stream is handled in coils carrying chilled water. Because temperatures below 40 F are rarely needed, water can do the job; brine is seldom used.

Since refrigerant expansion occurs outside the air stream, choice of refrigerant becomes wider. Piping for chilled water being relatively easy to install, such systems prove flexible in layout, well suited to large jobs.

**Coil Construction.** Chilled-water coils usually have nonferrous tubes, often with extended surface, Figs. 10, 11. Extended surfaces may be staggered or in line with air flow. Plain tubes are used where frost might accumulate.

Coil performance depends, among other things, on the way air flows over outside of tubes in relation to the way the heating or cooling medium flows inside them. Steam-heating coils, in which temperature within the tubes is practically uniform, are usually installed for cross flow of air. With chilled water in the coils, however, counterflow (water flow opposite to air flow) is almost universal. This gives highest mean temperature difference for entering air and water temperatures.

For much the same reason this scheme is used in coils fed with refrigerant. The higher entering-air temperatures help superheat the leaving refrigerant gas. With deep coils, however, the parallel-flow method (water flow in same direction as air flow) is used from the second row back. Circuit is completed by returning through the first row to get desired superheat from the higher air temperature there.

# Moisture Control

Important in the air-conditioning job is control of moisture content. Adding moisture is called *humidification,* and taking it out, *dehumidification.* Sometimes only one or the other of these operations is involved, but in most air conditioning we want to *humidify* at times and *dehumidify* at others. The *air washer* serves this purpose in many systems, along with cleaning the air and heating or cooling it. Let's look now at this multipurpose device and see how it works.

**Air Washers.** In essence, an air washer consists of a casing with one or more spray banks through which air flows. Usually there is some sort of eliminator at the outlet end to remove any entrained moisture from the leaving air. Spray water collects at the bottom. In passing through the sprays, air may be heated or cooled, humidified or dehumidified, depending on water temperature and the air's dewpoint, wet-bulb and dry-bulb temperatures.

As a starter on air-washer operation let's assume we're going to recirculate the spray water. When air and spray water come in contact, a heat exchange takes place — air gives up some of its sensible heat to vaporize some of the water. Thus its dry-bulb temperature is lowered. And with an increase in moisture content, dewpoint temperature rises. If those changes aren't entirely clear, refresh your memory on air properties by turning back to the first part of this special section.

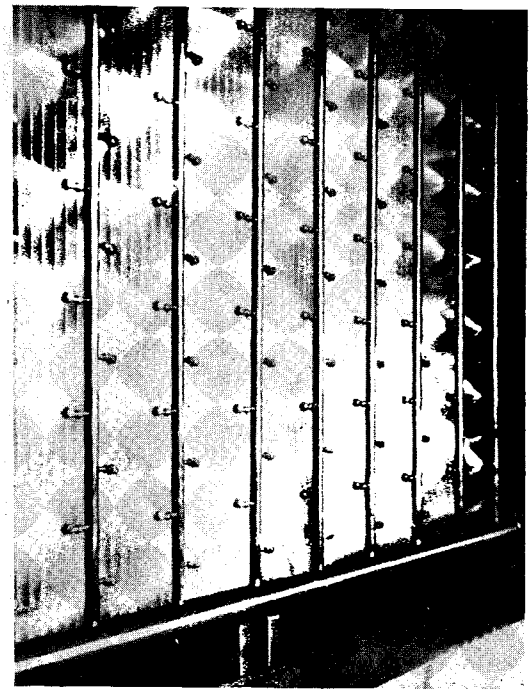
At the beginning, water temperature changes also, rising toward the wet-bulb temperature of the air. After a short time, operation levels off and water temperature stays constant.

**Washer Effectiveness.** If the air washer were perfect, here's what would happen: wet-bulb temperature of the air would be unchanged, while dry-bulb would drop down to equal it, and dewpoint would rise to equal it. Water temperature would also level off at this point. Thus the air would have been cooled and humidified.

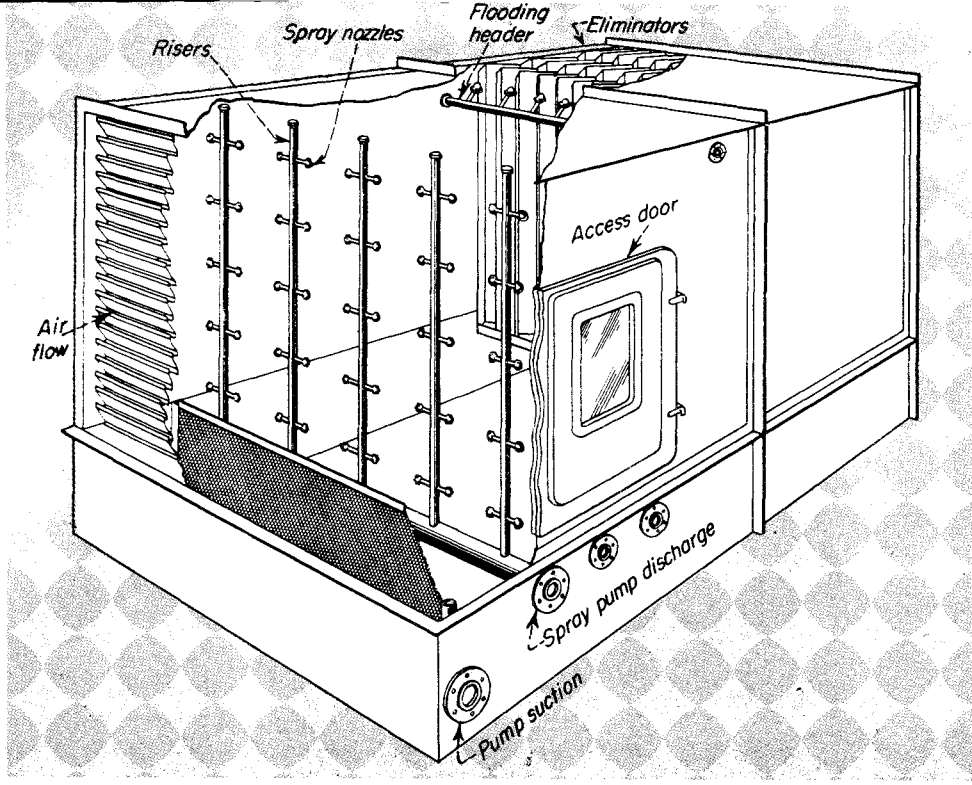
Since the washer's operation is not perfect, the dry-bulb and the dewpoint only *approach* the wet-bulb. How close this approach is may be used as a measure of the washer's effectiveness. It depends on the unit's general design and particularly on the number of spray banks. For a close approach two or more banks are needed.

This recirculation-type of operation is useful, but it's limited. By controlling water temperature we can fix the air conditions the washer produces. This means either blending fresh water into the washer circuit or passing the recirculated water through a heating or cooling coil outside the washer. Since the operations we're going to talk about involve heat transfer from air to water or water to air, water temperature will change during the process. What we're concerned with is the *final* water temperature; or the initial tem-

## WASHER CONSTRUCTION



**13** Main air stream passes through air washer, gets moisture content set




**14** Washer may have one or more spray banks, *left*. Supply header delivers water to risers and nozzles; spray saturates air so it nears wet-bulb temperature

perature and flow needed to hold it.

**Washer Operations.** Without going into detail, we can summarize possible washer operations as follows: (1) If final water temperature is held above entering-air dry-bulb temperature, we get both heating and humidification. (2) If we hold final water temperature below the entering-air dry-bulb, we get cooling and humidification. If water temperature stays below air wet-bulb, the same thing is true, and both dry-bulb and wet-bulb temperatures are lowered. (3) If we hold final water temperature below air's dewpoint, we get cooling and dehumidification.

Thus through the use of air washers we can exercise considerable control over the temperature and moisture content of the air. The necessary control of water temperature can be effected in any one of three ways: (1) recirculating only part of the spray water and adding to it hot or cold water as needed (2) pumping the water through a heating or cooling coil outside the washer, or (3) mounting a heating or cooling coil directly in the air-washer sump. In either (2) or (3) all water is recirculated.

**Washer Construction.** A basic need in any air washer is intimate contact between air and water. In most washers, Fig. 13-15, this is secured by breaking up water into small droplets in spray nozzles, like Fig. 16. Number of banks of sprays depends on the effectiveness desired; for dehumidification, two or more spray banks are usually installed. For good performance, air velocity through the washer chamber should be moderate (350-600 fpm), and there should be ample length of travel through spray zones. Effective moisture eliminators at the outlet end are essential.

Another means of securing intimate contact between air and water lies in use of wetted surfaces. Washer of Fig. 12 uses the capillary action of glass filaments to distribute thoroughly water sprayed across the surface. Air passing through the thoroughly soaked mass of glass fibers comes in close contact with the many wetted surfaces. This construction yields improved cleaning action, somewhat like that of a viscous filter.

**Surface Humidifiers.** In small installations and in room coolers, the pan-type humidifier may be used. Steam or electrically heated tubes in the bottom of the pan heat the water for vaporization. The air stream sweeping over the pan carries the moisture off with it.

**Direct Humidification.** Increasing humidity by adding moisture to the air stream on its way to the conditioned space is called *indirect* humidification. It is usually employed where humidity control is part of an over-all conditioning problem, as in the usual comfort system. In industrial applications, textile mills for example, a high relative humidity may be what's needed, with temperature control and ventilation only incidental. For such conditions, *direct* humidification — adding water directly to the air in the conditioned space — is often economical.

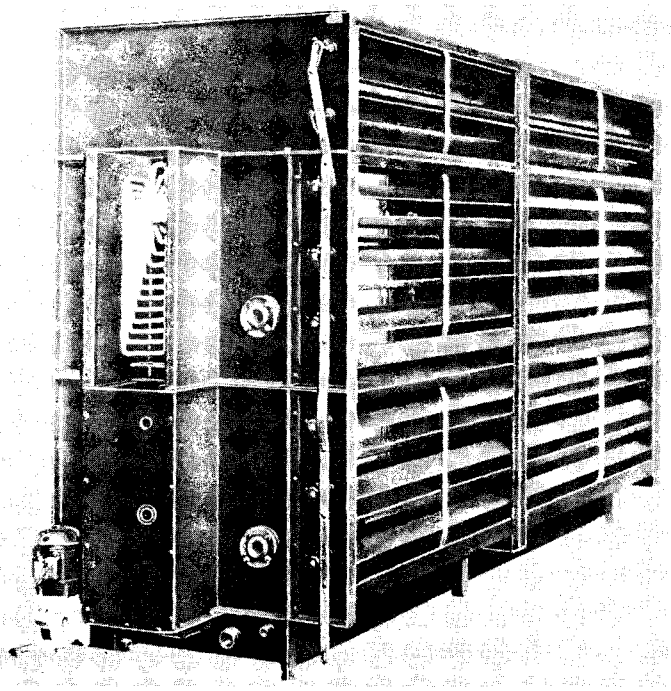
Nozzles for atomizing water so it can be readily converted to vapor by room heat may employ compressed air to aspirate water to the nozzle and atomize it, or may use air pressure in combination with water pressure. Such nozzles are located around the conditioned space.

In so-called high-duty humidifiers, water at high pressure (about 150 psi) passes through an impact-type nozzle mounted in a cylindrical casing. A fan above the unit forces air through it. This air, cooled and charged with moisture, escapes from an opening below, at high velocity and in a nearly horizontal circle. A somewhat similar design eliminates the fan. Aspirating effect of the spray nozzle induces an air flow through the casing. This helps to distribute the spray.

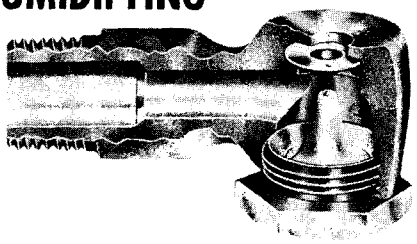
Working without compressed air, pumps or other auxiliaries, the centrifugal humidifier, Fig. 17, both generates and distributes the necessary fine spray. It is thus often called a self-contained humidifier.

**Dehumidifying.** There are basically two ways to dehumidify air: (1) cooling, and (2) chemical adsorption. Let's look at the cooling angle first. In talking about air washers, we saw that if final water temperature held below the initial dewpoint of the air, we got both cooling and dehumidification. We can see that the same result could be pro-

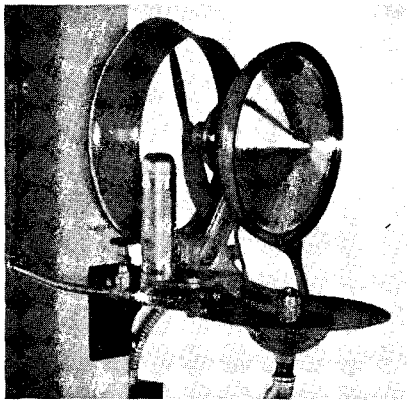
# WATER SPRAYS SERVE FOR HUMIDIFYING AND DEHUMIDIFYING



**15** **Air washers for dehumidification have at least two banks of sprays, Fig. 13. When used with direct-expansion cooling coil, spray water is all recirculated**



**16** **Spray nozzles in risers discharge at from 1¼ to 2 gpm each into air**



**17** **Centrifugal humidifier delivers fine spray into the conditioned room**

duced if we cooled the air by heat transfer to a coil carrying chilled water or expanding refrigerant, as long as coil temperature is below dewpoint.

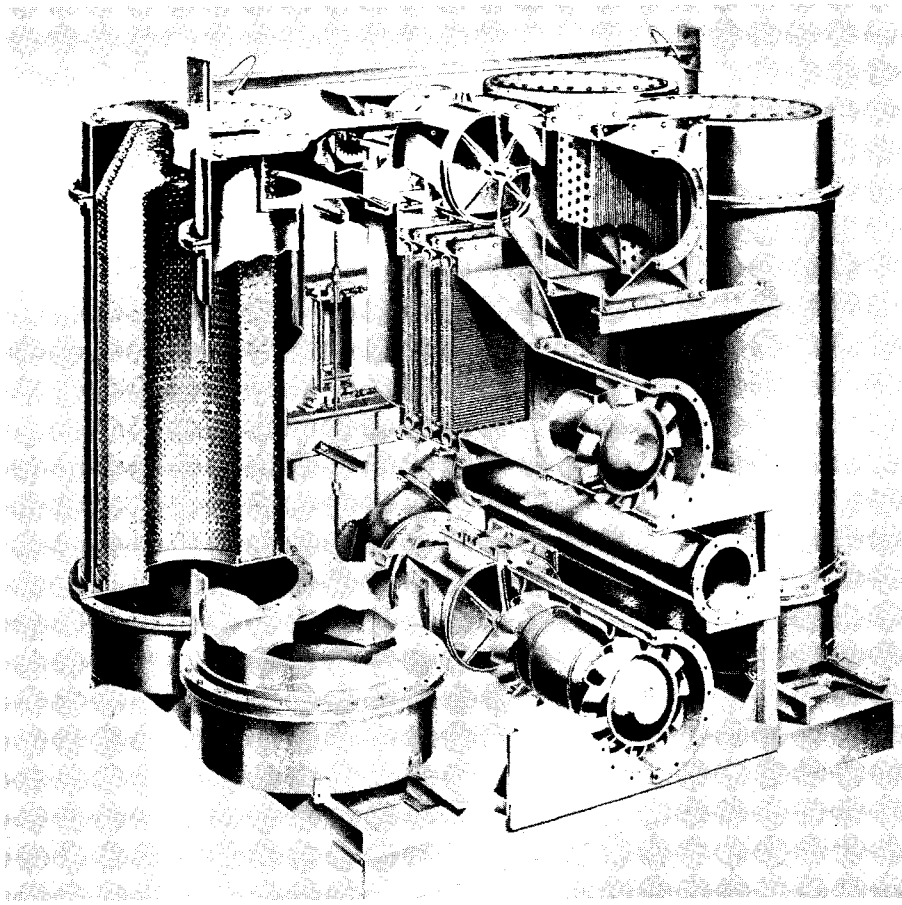
Cooling coils designed for dehumidification should have finned surfaces separated enough so moisture condensing on them can roll off. Drip pans and drains should be provided for the condensate. Since the air stream may pull condensed moisture off the coil surfaces, there should be some form of moisture eliminator on the discharge.

Whether a spray device, such as an air washer, or a cooling coil should be used for any given cooling and dehumidifying job depends on a variety of factors. In general, washers find use in the larger central systems, while the compact coils are widely adopted in unit or packaged air conditioners, and in small systems.

**Dehydration.** Dehumidifying, without removing heat at the same time, is sometimes called *dehydration.* In such an independent dehumidifying operation, latent heat in the entering air is converted into sensible heat in the leaving air. The job is done with *sorbents,* materials having the ability to extract and hold water vapor from surrounding air. Sorbents may be divided into two classes according to the way they behave in use: *adsorbents* do not change chemically or physically in the process, while *absorbents* change either physically, chemically, or both.

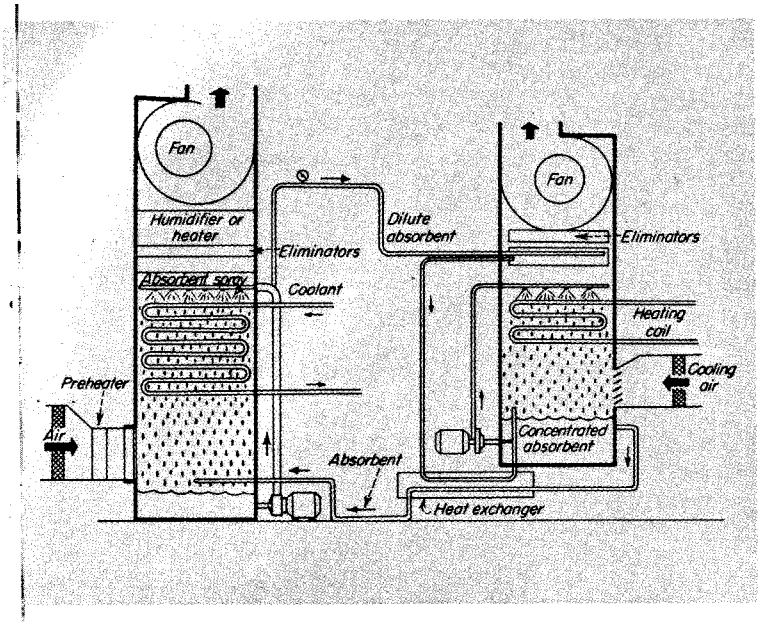
**Solid Sorbents.** Typical adsorbents are solids — activated alumina, silica

# MOISTURE MAY ALSO BE REDUCED BY SORBENTS

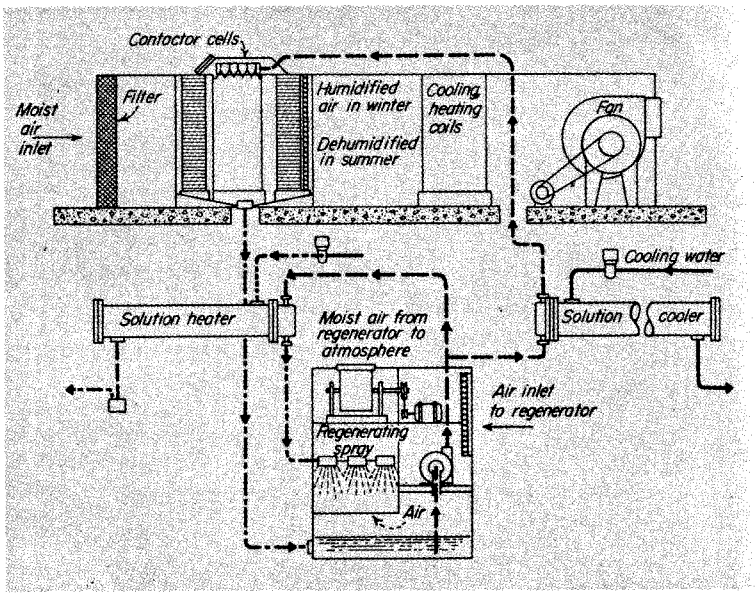


**18** **Solid sorbents, in this case silica gel, remove water from air if vapor pressure in sorbent is below that of air. One bed is reactivated while other works**

# THESE DEHUMIDIFIERS USE LIQUID SORBENTS TO REGULATE MOISTURE




**19** **Tower, *left*, fixes moisture content of conditioned air; at *right*, sorbent gives up water and is reconcentrated**




**20** **Pump draws sorbent from regenerator: about 85% goes to cooler, spray nozzles; rest is reheated, concentrated**

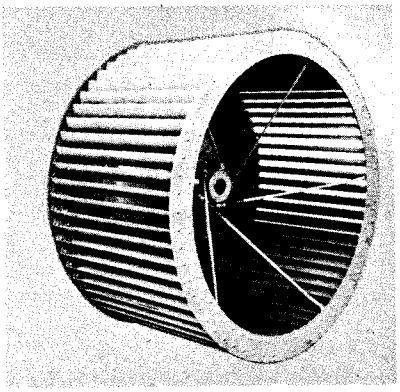
gel, activated carbon, bauxite. These remove water from an air stream only if vapor pressure of the water in the adsorbent is less than the partial pressure of the water vapor in the surrounding air stream. In other words, the process is primarily one of condensation. The latent heat of vaporization and heat of adsorption have to be taken away by the surroundings. Thus the air stream, the adsorbent itself, and the adsorbent container, all increase in temperature. Eventually the sorbent temperature reaches a state of equilibrium and the material has to be reactivated — heated to drive off the adsorbed moisture and cooled down for re-use.

Usual equipment for solid sorbents employs a single or dual bed depending on how important it is to maintain continuous dehumidification. In small installations, and where a short-time outage for reactivation is not too important, the single-bed units may be used. Fig. 18 illustrates a typical dual-bed arrangement for continuous operation. Air enters through a bank of filters and reaches an adsorbent bed. While this bed is working the other is being reactivated — heated to about 300 F. Heating may be done by steam coils, electricity, waste flue gas from gas or oil fires.

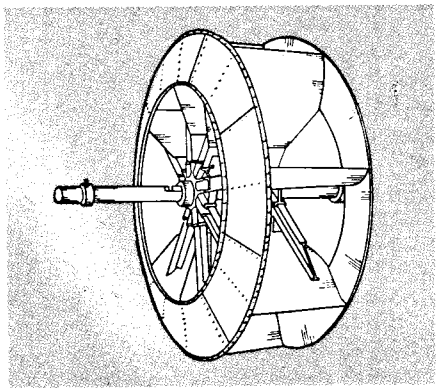
**Liquid Sorbents.** Typical absorbents are liquids — solutions of the halogens (lithium-chloride, calcium-chloride and lithium-bromide) and the glycols (mostly ethylene, diethylene and triethylene glycol). These solutions must have concentrations such that their vapor pressure with respect to water is lower than that of the water vapor to be removed from the air. In the typical liquid-sorbent equipment, air passes through a tower into which the liquid sorbent is sprayed either in a fine mist or as a blanketing solution on the tower surfaces. Again, differences in partial pressure determine the absorption. Soon a state of equilibrium is reached. The sorbent solution, the air, and the equipment increase in temperature as latent and chemical absorption heats are taken up.

The warm, weak sorbent solution is first cooled. Then part is diverted for concentration. This is done by heating to a vapor pressure well above that of air blown over it; water in solution

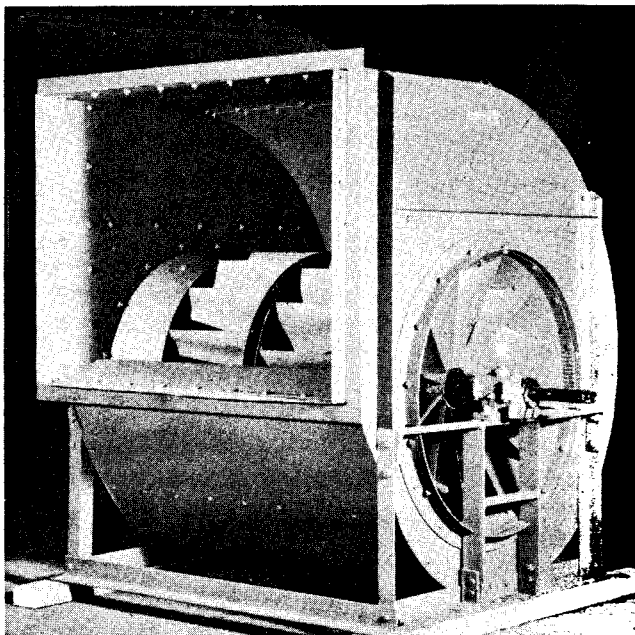
# CENTRIFUGAL FANS FIND WIDE APPLICATION



**21** **Typical multiblade wheel for centrifugal fan unit**



**22** **So called "plate" construction may also be used for centrifugal wheels**



**23** **Inlet vanes iron out turbulence in the air stream and decrease noise**

goes off with the air. After cooling, the concentrated solution rejoins the main stream to maintain proper density, the principal factor determining water absorption by liquid sorbents. Fig. 19 and 21 show typical equipment for dehumidification by use of liquid sorbents.

Chemical dehumidification finds use primarily where moisture removal is the major consideration. Where sensible as well as latent heat must be removed, chemical units may be combined with cooling equipment. Whether such a combination works out better than the conventional cooling-dehumidification depends on a number of factors. Conditions favoring use of chemical dehumidifiers are: (1) availability of cheap cooling water for sensible heat removal (2) cost of gas or steam low in relation to cost of electricity, and (3) load that is mostly latent heat.

# Air Distribution

Having cleaned our air, and adjusted its moisture and temperature, our next job is to move it to the points where it is to be used and to distribute it in the conditioned spaces in the proper amounts and without drafts.

Air movement begins with fans. They develop the necessary pressure head to overcome resistance to air flow. Then we have ducts — trunk ducts and branches — for guiding air to its destination. Finally we have outlets, grilles, registers, diffusers for introducing the air into the conditioned space.

**Fan Types.** Air-conditioning fans may be divided into two groups: (1) the familiar *centrifugal* designs, whose flow is essentially at right angles to the axis, and (2) *axial* designs, whose flow is parallel to the axis.

Typical centrifugal fan consists of a wheel with blades at its rim, the whole rotating within a housing shaped like a scroll. Shape and direction of the blades has a great deal to do with fan performance. There are three basic types: (1) forward-curved blades have the tip inclined in the direction of fan rotation (2) radial-curved blades have a straight, radial tip, and (3) backward-curved blades have tips inclined opposite the direction of rotation.

Each of these blade shapes produces distinctive performance characteristics. The forward-curved blade is widely used in air-conditioning and ventilation because it: (1) is more compact for given air delivery and static pressure, and (2) operates at lower tip speed and is thus apt to be quieter. Backward-curved type operates at relatively high speed but has steep pressure curves and non-overloading power characteristics. It is well adapted for direct motor drive and for systems in which demand fluctuates widely.

In the form of the "propeller" fan, the axial type is familiar for applications where pressure is relatively low. Recent designs of axial fans will deliver against pressures as high as 9 in. of water, making them suitable for working with some duct systems. As a class, axial fans have high efficiency and non-overloading power characteristics. Because of the straight-through flow, they offer possibilities of ductwork simplification.

**System Load.** When you put together the necessary ductwork, heating and cooling coils, filters, etc that make up an air-conditioning system, you have set up a fan load that is highly individual to that system and to which the fan must be matched. The resistance a system offers varies nearly as the square of the air volume flowing through it. When you superimpose system and fan characteristic curves, operation is at point common to both.

**Ductwork.** When it comes to sizing ductwork, it must be kept in mind that type of equipment as well as its purpose influences the air-transmission system. For instance, in some systems, air is moved at high velocities to save ductwork costs and space. In others, lower velocities may prove desirable.

Ducts are usually made of galvanized steel, frequently a copper-bearing alloy for corrosion resistance. Insulation may be desirable on long runs and where heat pickup may be large. There are also prefabricated duct sections of laminated asbestos, Fig. 27.

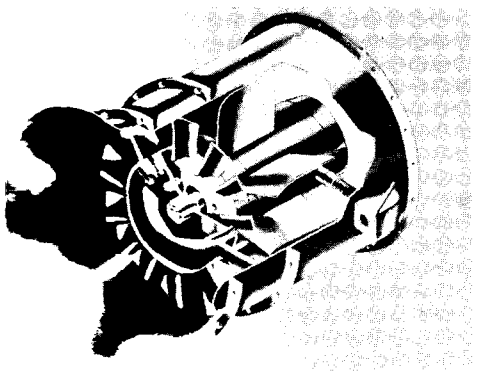
**Air Distribution.** Securing proper distribution of air within a large room without creating drafts is difficult. Any air movement at a rate above 30 fpm in a room of seated people may seem uncomfortable to many. If the temperature and relative humidity are within comfort-zone limits, somewhat higher velocities can be tolerated. And where people are moving about, velocities as high as 120 fpm can be used. Air can be withdrawn through grilles at up to 70 fpm without discomfort.

Over and above precautions taken to prevent undue drafts is the desire to get even distribution despite the fact that incoming air may be different in temperature from the room air. Furthermore, some means of controlling air quantity at room inlets may be desirable. Thus a considerable variety of grilles and diffusers are available, Fig. 28-31, incorporating features designed to solve these problems.

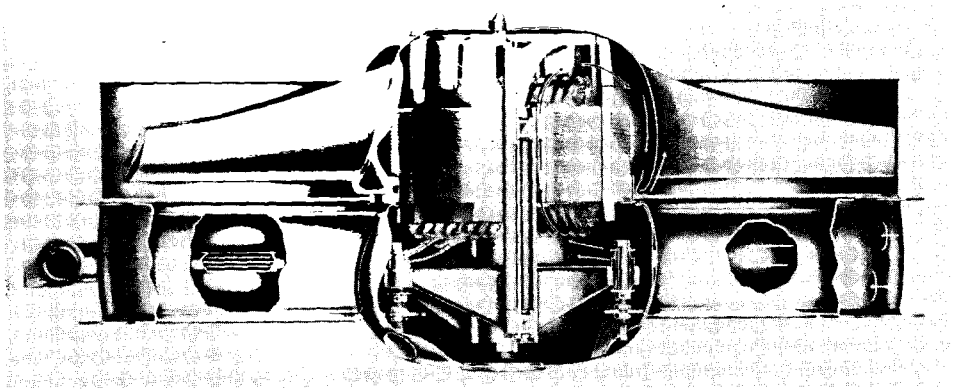
# Refrigeration

In the foregoing, we have talked of heating and cooling operations without reference to the source of heat and "cold." For heating, of course, we use some form of steam or hot-water boiler. Such heat sources are covered in

## AXIAL FANS MAY SIMPLIFY INSTALLATION OF DUCTWORK IN FAN ROOMS

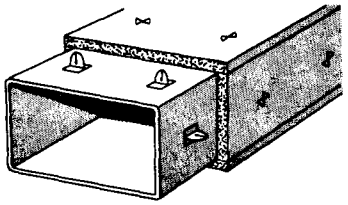


**24** This axial fan has adjustable inlet blades to compensate for resistance

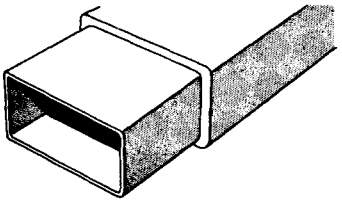


**25** Large air volumes can be moved against relatively high resistance with axial fans; design shown above has motor built into the hub, relatively short blades

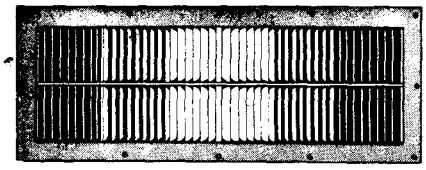
# DUCTS DELIVER AND OUTLETS DISTRIBUTE AIR



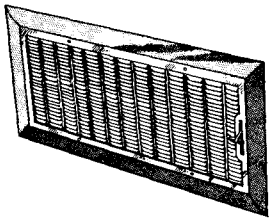
**26** **Ducts, commonly made of galvanized steel, may need insulation**



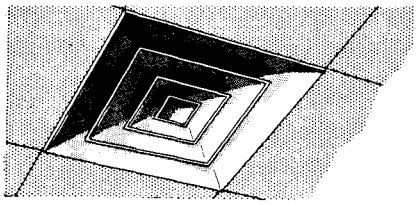
**27** **Ducts may also be prefabricated of laminated asbestos, as shown above**



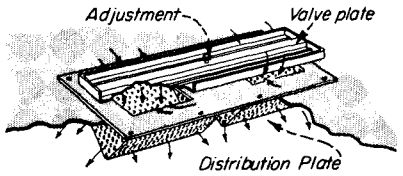
**28** **Grille has deflecting vanes so any desired air pattern can be set up**



**29** **An adjustable damper permits varying the volume of entering air**



**30** **Latest diffusers mount flush with ceiling, blend with the decorations**




**31** **Valve plate and distribution space slow air down, smooth out the flow**

POWER's special sections "Steam Generation" (Dec 1946) and "Fuels and Firing" (Dec 1948). Here we propose to concern ourselves briefly with sources of cooling, leaving detailed treatment to a future special section on refrigeration.

**Cooling Sources.** In some cases, water may be available from natural sources (wells, for example) at temperatures low enough for use in an air-conditioning system. Where well water cannot do the job by itself, it may serve for part of the job — precooling, for example. In most cases, cooling must be provided by refrigeration machinery.

Most refrigeration systems depend on the fact that vaporizing a liquid requires a relatively large amount of heat and the further fact that the temperature at which vaporization (and the reverse operation, condensation) takes place depends on pressure. By juggling these factors, we can vaporize our *refrigerant* and extract heat at some low temperature, and can condense it back again at a higher temperature. This means that we can do the cooling needed for condensation with, for example, water at readily available temperatures — say 70-80 F.

**Compression Cycles.** In the most familiar type of refrigeration, we use some form of mechanical compressor to make the pressure changes we need. In such a cycle, Fig. 32, we work with a refrigerant that boils or vaporizes at a relatively low temperature. Allowing this liquid to vaporize in an *evaporator,* or direct-expansion coil, extracts heat from the surroundings. We then take refrigerant gas at low pressure and compress it to a higher level — high enough so that water at some handy temperature, say 80 F, will condense it back to the liquid form.

The essential parts of a compression system are thus a compressor, a condenser, a receiver for storing liquid refrigerant, an expansion valve, and an evaporator or expansion coil. Compressors may be of reciprocating or centrifugal design, usually driven by motor, sometimes by a steam turbine or an internal-combustion engine. Condensers in modern plants are usually of shell-and-tube construction. For capacities up to about 100 tons of refrigeration, so-called condensing units are available. These combine the compressor, condenser and receiver in a package, sometimes hermetically sealed.

For reciprocating compressors, the most widely used refrigerant in air-conditioning work is Freon-12. Ammonia offers many thermodynamic and practical advantages and is used widely in industrial applications where economy is important and precautions can be taken against the hazards of ammonia's toxic properties. Methyl chloride finds uses in smaller units. Carbon dioxide, while considered a "safe" refrigerant, is not often used today because the required high pressures mean heavy equipment and high power consumption.

Centrifugal compressors, suited, in general, for lower operating pressures, often use Freon-11, which has desirable pressure characteristics.

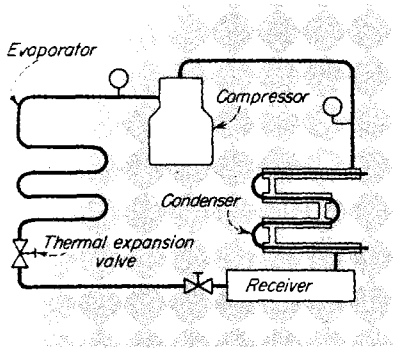
**Steam-Jet System.** Although we do not usually think of it, water may be used as a refrigerant. It is, in itself, cheap, and completely safe. Because extremely low pressures (actually high vacuums) are needed, the usual apparatus employs steam ejectors. Fig. 33 shows such a system. In the evaporator, which is under high vacuum, part of the water flashes into steam, cooling the rest of the water. To maintain the vacuum, ejectors draw off the vaporized water and entrained air and compress them to a higher absolute pressure. The compressed vapor and the "power" steam are then condensed. This condenser requires considerably more cooling water than the condenser for a conventional mechanical compression system, since it must remove the heat of the power steam as well as that liberated from the chilled water. Such systems find use where condenser water is plentiful and steam cheap.

**Absorption Systems.** In these systems, heat is used in place of mechanical work for changing refrigerant pressure. The compressor is replaced by three devices: an *absorber,* a *pump* and a *generator,* Fig. 34. After expansion in the evaporator, the refrigerant goes to the absorber and is taken up by a low-temperature absorbent fluid This solution is pumped to the generator, where heat is supplied to drive off refrigerant as a gas. This is condensed to a liquid, as in a mechanical system, and goes to evaporator for expansion.

Absorption systems of the past used ammonia as refrigerant, it being readily soluble in water. Other combinations have been employed, particularly in gas- or oil-fired domestic refrigerators. A recent development uses lithium-bromide salt and water, with water acting as the refrigerant. The boiling point of the salt, a solid at ordinary temperatures, is so high it behaves like a non-volatile substance. There is thus no vaporization of the absorbent in the generator and no carryover of the absorbent vapor to the condenser. The characteristics of the absorption cycle limit its usefulness to places where sources of heat and cooling water are plentiful and cheap.

**Ice Systems.** Some installations, such as churches and theaters, have short operating hours and relatively high peak loads. Investment in mechanical refrigeration equipment would thus run high. In some such cases, ice proves the answer. A comparatively small quantity of ice in the water-

# VARIETY OF REFRIGERANTS AND REFRIGERATING SYSTEMS AVAILABLE



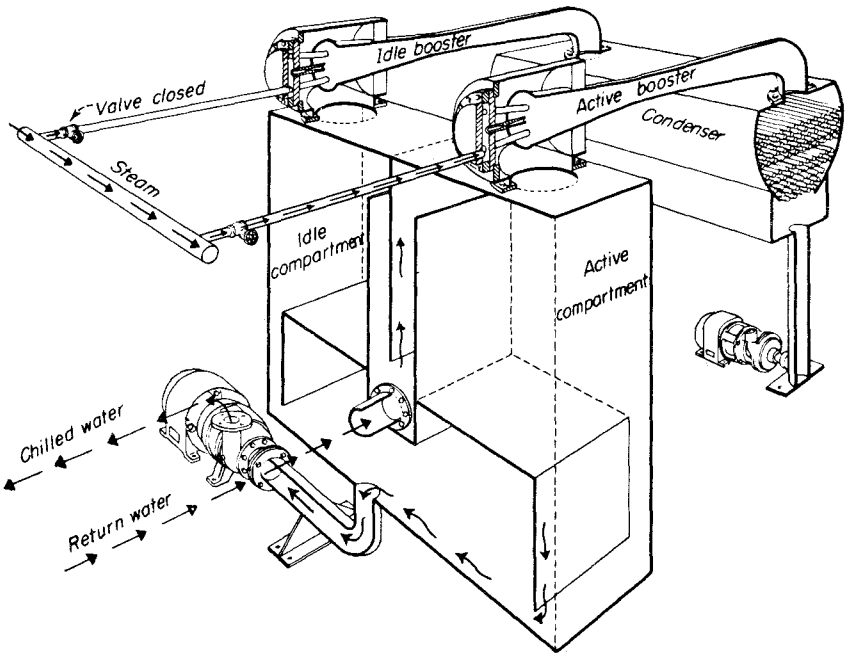

**32** **Diagram shows elements of familiar compression refrigeration cycle**

cooling tank of such an installation, Fig. 35, can release refrigeration at a rapid rate.

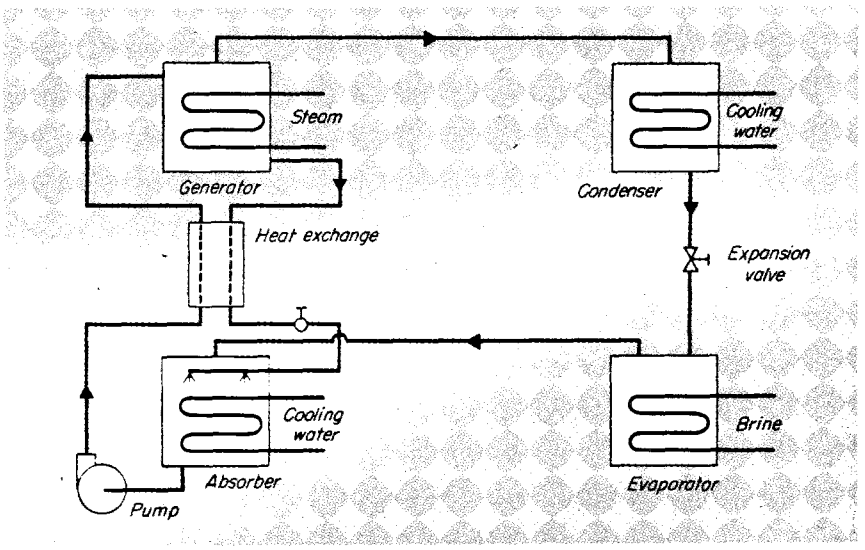
**Cooling Water.** Virtually all refrigeration systems require water for condensers. For a fortunate few, natural water supplies—wells, rivers, lakes, etc.—are available. In many areas, however, public water supplies must be used. Both for reasons of cost and, in recent years, increasing shortness of supply because of skyrocketing demands, conservation is essential. This leads to use of some form of evaporative cooling, in which air does most of the work and water consumption is sharply cut.

Cooling ponds and spray ponds are seldom used in air conditioning. Cooling towers and evaporative condensers prove the usual answer. In essence, a cooling tower consists of a casing which may be filled with spray or with a packing over which the water falls in thin films. The objective in either case is to bring about intimate contact between water and air passing through the tower. Evaporation of a small part of the water, say about 5%, cools the rest. Some towers are of the atmospheric type, using natural draft; most, however, employ mechanical draft, either forced or induced. This yields a more compact and efficient tower. The water to be cooled may be run through the tower, or may pass through a heat exchanger cooled by the tower water, which is recirculated. Larger towers are usually installed outdoors, frequently on building roofs. Smaller towers are designed in some cases for indoor installation.

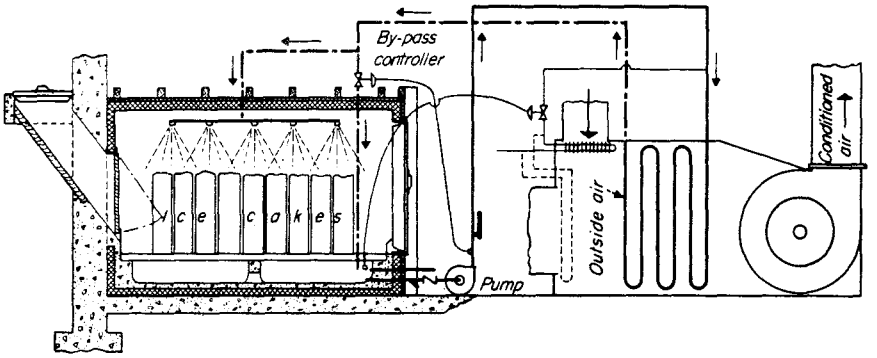
The evaporative condenser consists of a steel casing housing coils over which a water spray falls. A fan forces air through the casing at high velocities. Evaporation of part of the water removes heat from the fluid in the pipe coils. This may be condenser water but usually refrigerant gas itself passes through the coils.



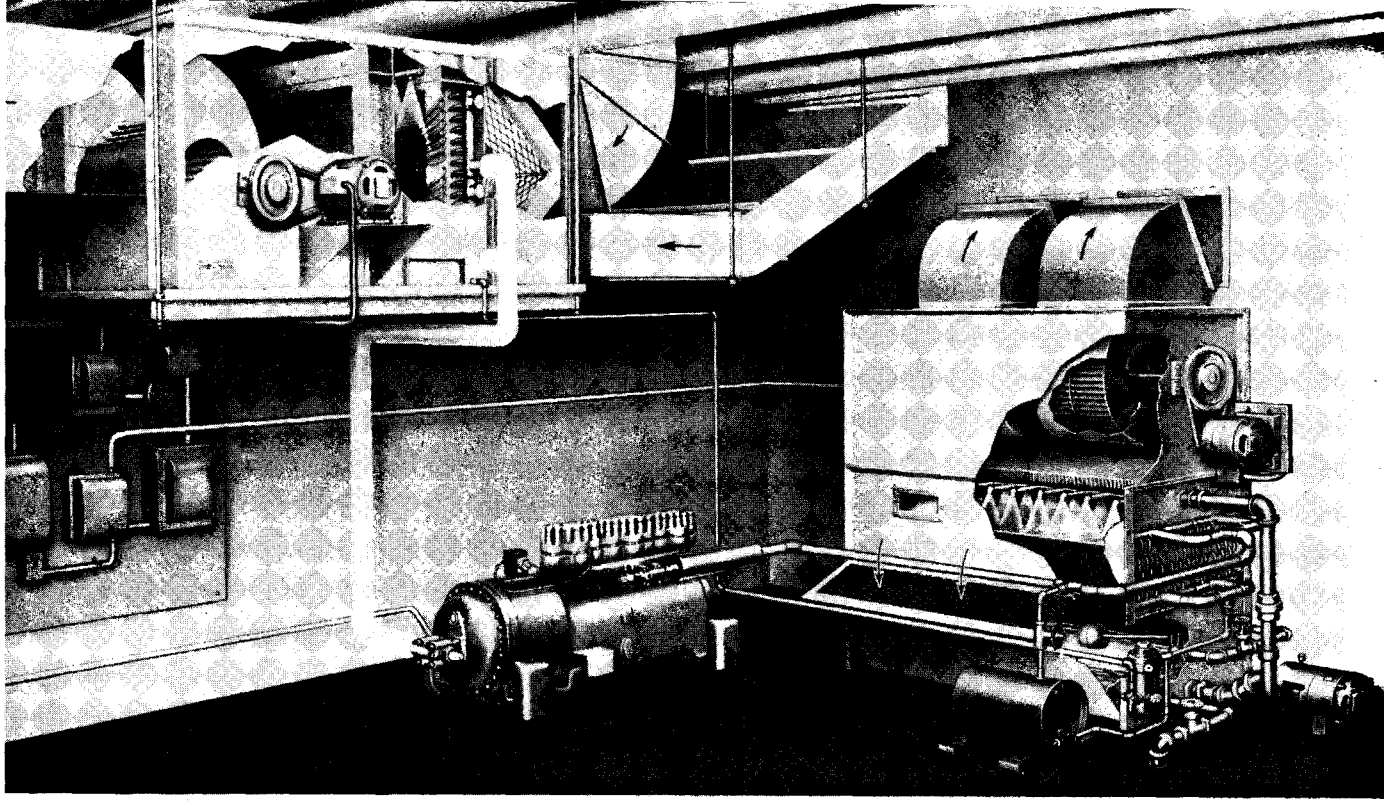

**33** **In steam-jet refrigeration system, water is really the refrigerant. Ejector establishes vacuum, causing part of water to vaporize; this chills the rest**




**34** **Absorption system of refrigeration uses a low-temperature liquid to absorb vapor from the evaporator; refrigerant is boiled off in the generator section**

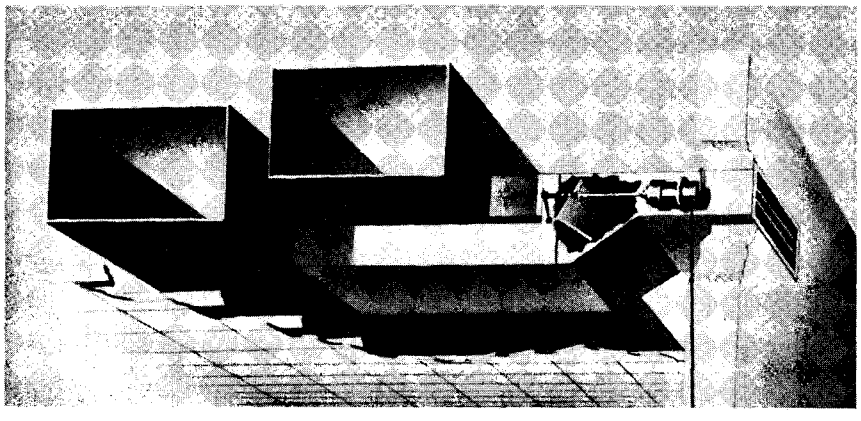



**35** **Cooling job can also be handled by melting ice. Melted ice and a controlled quantity of spray water circulate through the cooling coils in the air stream**

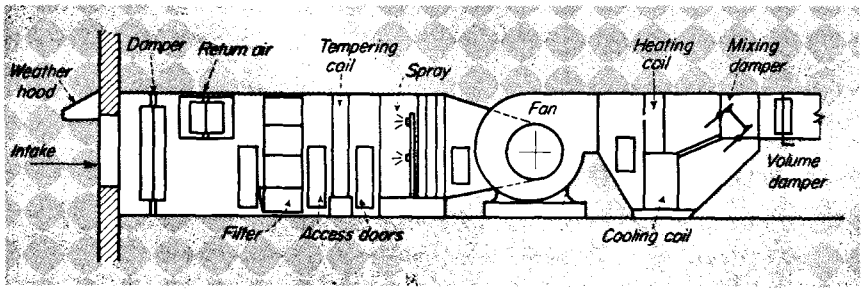


**1** Central system using a remote apparatus room for all the elements involves low investment where air-conditioning load is high. Maintenance and inspection can be carried out with least disturbance to occupied zones; space costs little

# How to Fit Equipment to



**4** Double-bladed mixing damper in takeoff from two separate ducts, one carrying cold air and the other hot, blends air to give the desired room temperature



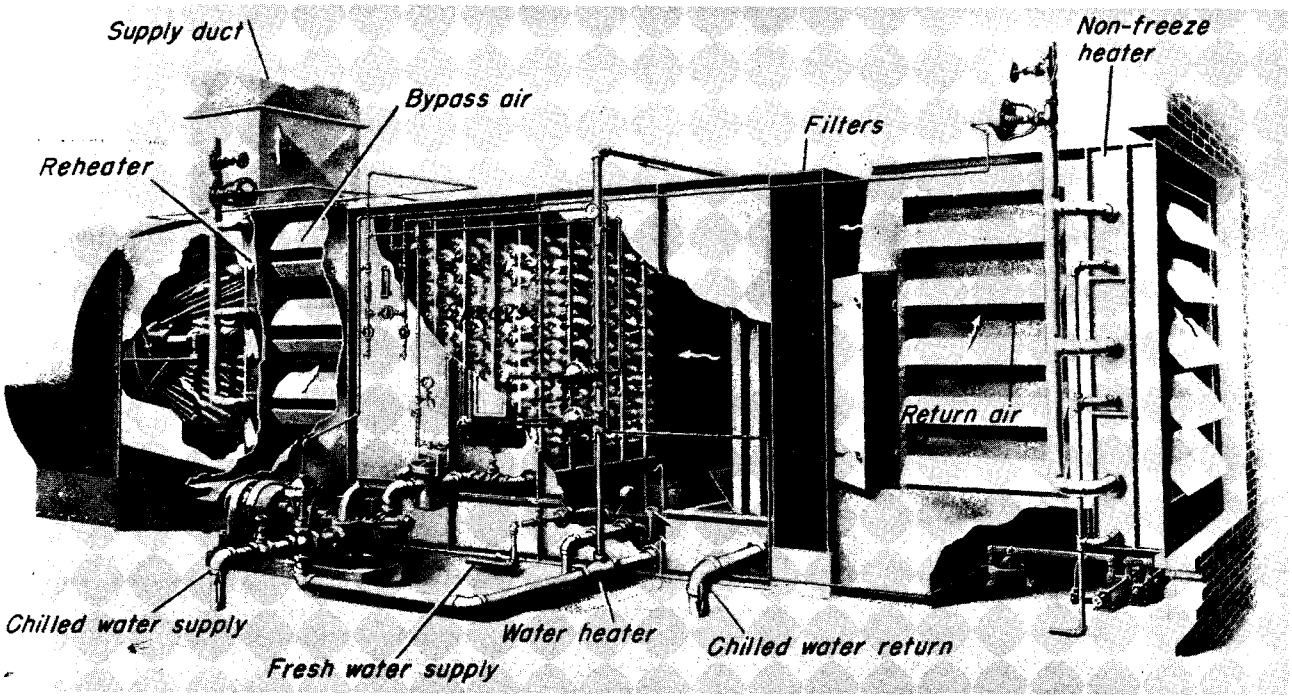

**5** For use with the control setup shown in Fig. 4, this central system supplies conditioned air at one temperature to one duct, at lower temperature to other

Up to now we've talked about the things that make air conditioning possible — the properties of air and the tools available for putting these properties to work. We're now ready to button up the story by showing how the various elements may be combined to meet the needs of different jobs.

Behind each choice of a combination is the question, "What arrangement gives the most economical answer?" In larger plants, some form of central system may pan out best; for smaller setups, there are packaged units and room conditioners. In some buildings, air conditioning combines with an existing heating plant, with the heating equipment handling the "cold-wall" load of outside walls and windows. This so-called "split" system has also been used in a number of new buildings, employing radiant heating in walls or ceilings. In a couple of current cases, radiant coils will carry some of the cooling as well as the heating load.

**Central Systems.** In the true central system, all major equipment — filters, air washer, fans and refrigeration machinery — are centrally located, removed from the area to be conditioned. Ducts distribute conditioned air to the various occupied spaces. Advantages claimed for such a system include:

# CENTRAL PLANT DELIVERS CONDITIONED AIR THROUGH DUCT SYSTEM




**2** Central plant, above, shows all the conditioning elements needed for central air distribution except refrigeration

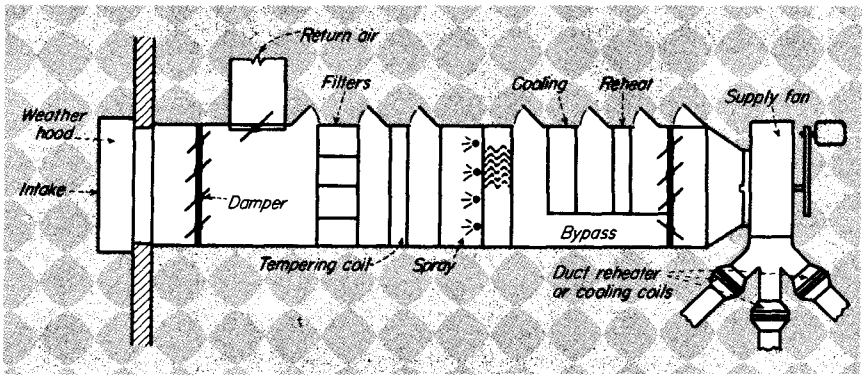
**3** Conditioned air from central system, *below*, is delivered to zones by separate ducts, with reheat or cooling coils

# the Job

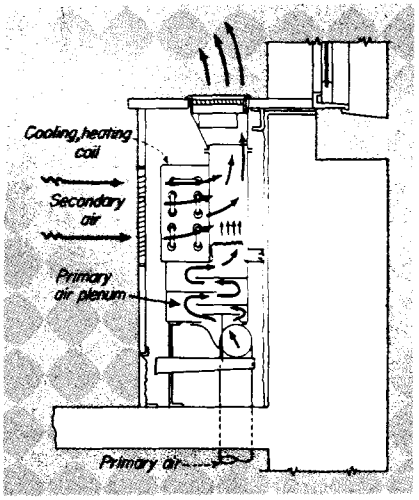
(1) It occupies space of relatively little value compared to conditioned areas. (2) Where the air conditioning load is fairly large, investment cost may be less than for other possible arrangements. (3) Maintenance and inspection are carried on with little disturbance in conditioned areas. (4) Exhaust air can be returned and partly reused with obvious savings in heating and refrigeration.

Major drawback to such a system is the space taken by ductwork, often impossible to secure in existing buildings. Ductwork is also expensive. This leads to modified forms of the central system. In the commonest of these, refrigeration and heating is handled centrally, and the cooling and heating mediums distributed to local conditioning equipment serving individual floors or areas.

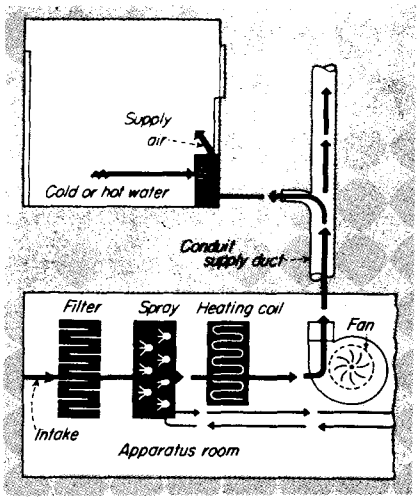
**Typical System.** Fig. 1 shows a typical central-system apparatus room. Large duct, *upper right*, carries incoming fresh air. Ductwork coming down from upper floors brings back return air. Air from these ducts meets and mixes in proportions regulated by mixing-damper setting. Air then passes through a filter bank and back over direct-expansion coils. These coils both cool and dehumidify. Right behind




## HIGHER AIR SPEEDS PERMIT SMALLER DUCTS

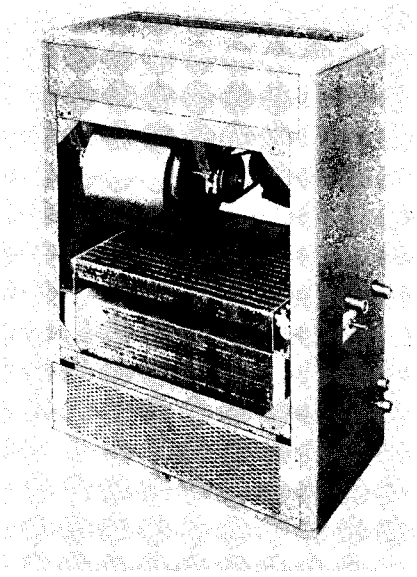


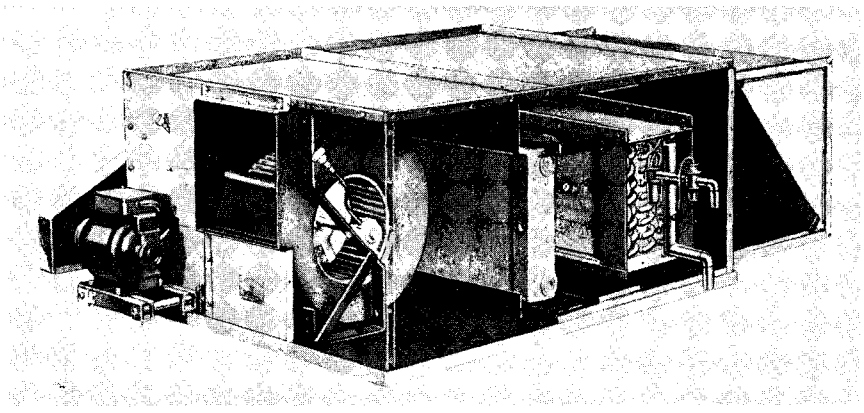

**6** Room convector takes high-velocity air, mixes with room air as needed




**7** Supply and return distribution system for room convector shown, *left*

# SUPPLIED BY A CENTRAL PLANT, THESE UNITS HANDLE LOCAL AREAS

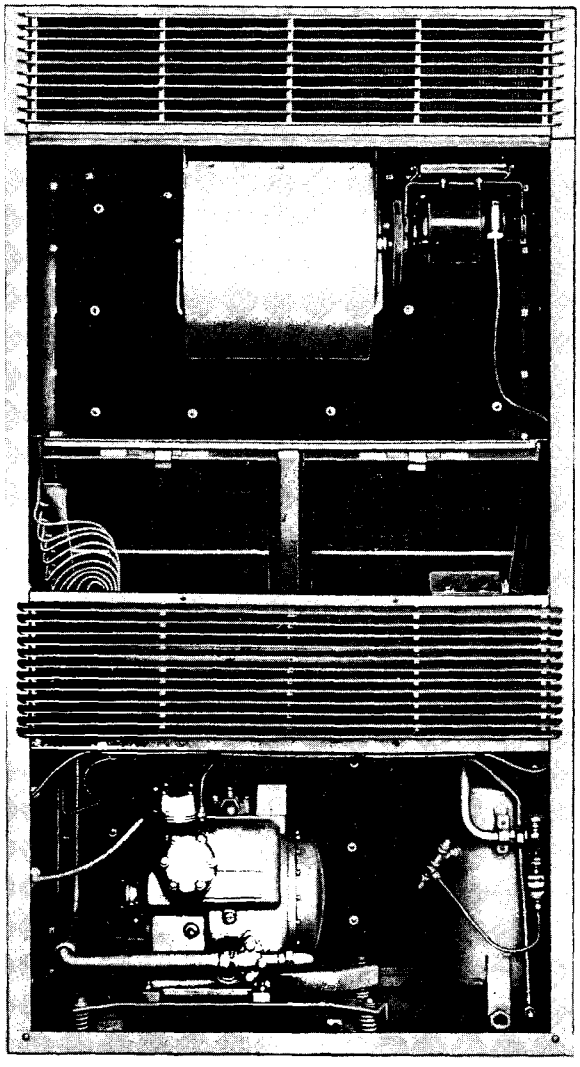




**8** **Packaged air-conditioning assembly, *above*, is complete except for refrigeration. Such units serve as air-distribution centers supplied by central refrigeration**

**9** **Smaller unit conditioners of same principle as Fig. 8 design, *left*, may be spotted through the plant. Need only electricity, air and refrigeration connections**

# PACKAGED CONDITIONING EQUIPMENT



**10** **Complete air-conditioning assembly, including refrigeration, gives central system in packaged form; may carry floor load in old building, save supply duct**

them is a spray system for further adjustment of moisture content. In winter, when moisture must be added to the air, the spray does the job. A reheat coil follows, to set final relative humidity and meet variations in sensible-to-latent-heat ratio.

Along the right wall is an evaporative condenser for the refrigeration unit (*center*). Note that air supply and exhaust for the evaporative condenser are entirely separate from air supply for the conditioning system.

**Larger System.** A somewhat larger plant shows in Fig. 3. It draws in outside air from the left, preferably from an intake on the building side least exposed to solar heat, and not too close to the ground or a roof. A proportioning damper interlocks with a damper in the return duct to control ratio of fresh to return air. Usual scheme is to key these dampers so, as outside air increases, return air decreases, and vice versa. Then the mixed air streams pass through a filter bank.

Cleaned air is then ready for temperature- and moisture-control stages. Systems using air washers, see Fig. 2 also, usually pass air over a tempering coil to make sure its temperature is above freezing point. During most of the operating time, enough return air goes back with the incoming fresh air to avoid any freezing in the washer. This unit serves as a spray humidifier in winter months, and may be used as a dehumidifier in summer.

In the layout of Fig. 3, air from the tempering coil goes directly into the washer for humidification as needed. After the washer there are cooling and reheating coils, with a bypass around them into the main supply fan. Note

provision for reheating or cooling coils in branch ducts.

Fig. 2 shows a practical arrangement of the air-conditioning elements—tempering coils, filters, washer, etc. It delivers conditioned primary air for distribution through a central duct system.

**Zoning.** In a large structure, such as an office building, hotel or industrial plant, conditions vary from one part to another. Air conditions that are right on the sunny side, for example, are wrong for the shady side. Thus areas are usually broken up into zones, each fed by separate ducts. A number of different means are used for supplying correctly conditioned air for the various zones.

One scheme would be to regulate quantity of conditioned air entering a given zone — that is, proportioning the flow according to the different zone loads. But the control mechanism — usually throttling dampers — presents some problems and this method is not generally recommended.

**Booster Heaters.** A better hookup uses properly proportioned heating and cooling coils (Fig. 3) in branch ducts leading to individual zones. These are supplied from the central heating or cooling equipment. With these heaters exact adjustments in dry-bulb temperature can be made for each zone.

In a variation of this system, each branch duct has a separate small supply fan, with the reheating and cooling coils on the suction side. These fans should be of backward-curved non-overloading design so they won't tend to fight each other for the air supply and upset air distribution.

**Blending Air.** Fig. 4 and 5 show another arrangement. Supply fan is right behind the air washer, which is bypassed in hot weather. Supply fan discharges through a split duct. The top part has a heating coil, the lower, a cooling coil. Air leaving these coils goes into separate chambers, with branch ducts running from them. "Hot" and "cold" ducts run side by side. At each takeoff there is a double-bladed mixing damper under control of a room thermostat or other control device. This blends warmer and cooler air as needed to give desired conditions in each occupied space.

In the particular system shown, the cooling coil carries no refrigerant in winter, and the heating coil no heat in summer. Since the air leaving the warm chamber may be high in relative humidity it may not compensate for the nearly saturated cool air. Closer control over relative humidity may be obtained by a reheater in the cold-air chamber for summer service.

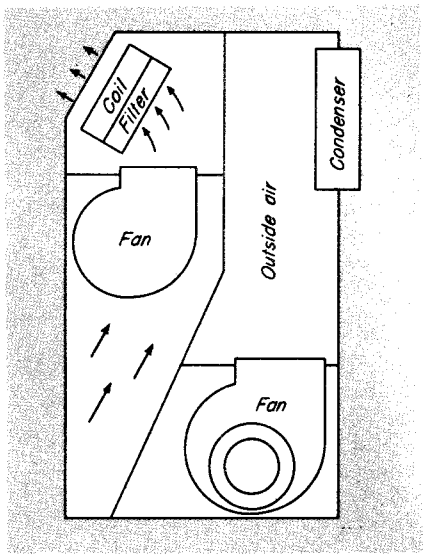
**Booster Fans.** In a widely used hookup, there is a booster fan between main air supply and each occupied zone. There is no return of air to the central conditioning equipment, which handles all fresh air. A takeoff with a double mixing damper connects each booster fan and the main duct. This mixing damper interlocks with an outlet exhaust damper in the return-air plenum for the zone. As more zone air is recirculated and the main air duct supplies less, exhaust damper closes in proportion so less air spills to waste. Thus local recirculation and mixing effect control.

In many hotels and offices, the booster-fan system serves individual floors as separate zones. The fan itself is usually in a fan room off the main corridor, which serves as a return-air plenum.

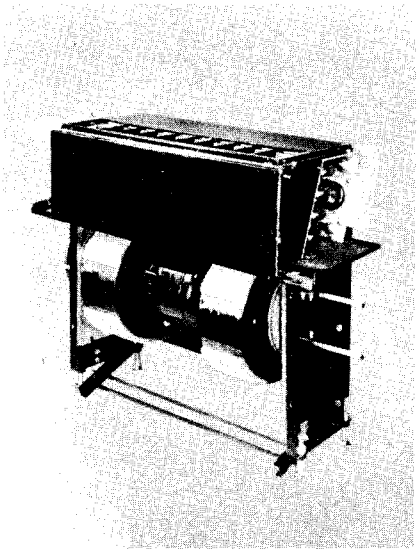
**High-Velocity System.** For economy of space and installation cost, one system distributes conditioned air at high velocity through relatively small conduits. These serve what might be called induction convectors in each conditioned space. The high-velocity conditioned air, Fig. 6, acts as a jet to induce room air to mix with incoming conditioned air. The mixture sweeps over a heating or cooling coil for final conditioning. Water supply and return lines supplying these coils parallel the air conduits, which are furred-in along outside walls.

Same induction principle is applied in smaller buildings, using supply and return ducts instead of high-velocity conduit. Both sensible and latent-heat cooling is done centrally. Control of summer room temperature is accomplished locally by regulating amount of conditioned air admitted to the induction convector. Convector unit has a heating coil for winter operation.

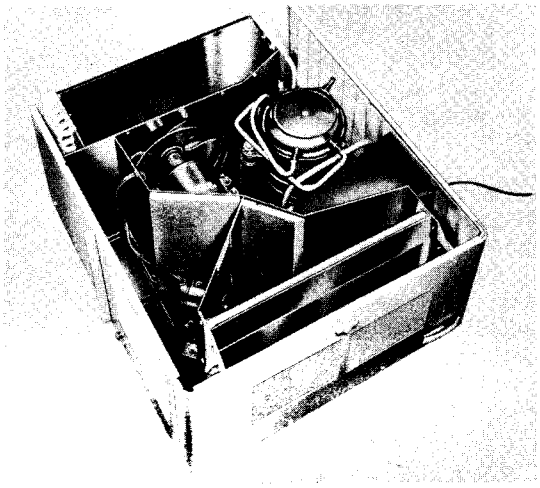
**Package Conditioners.** Recent years have seen the development of packaged systems for smaller installations. A typical unit, Fig. 10, contains in its




**11** **Floor model has refrigeration, conditioning equipment on inside**



**12** **This room air conditioner depends on an outside refrigeration supply**



**13** **Complete, self-contained window units require only an electrical plug-in to go to work. Usual design has the conditioning elements inside, refrigerating outside**

housing all essential elements for conditioning — refrigeration machinery, filters, cooling coils, fan and mixing plenum. Only connections needed are for water, drainage and electricity.

Such packaged conditioners may stand in the conditioned space, or serve a small duct system connecting several areas. Used in sufficient numbers, they meet the needs of existing buildings where installation of a conventional central system might be difficult or expensive. They prove an ideal answer, of course, for small buildings, stores, isolated spaces, etc.

**Local Conditioning.** In one of the most widely used modifications of the basic central system, only the refrigeration is handled at a central point. Chilled water or refrigerant for cooling, and a heating medium if needed, are circulated throughout the building instead of conditioned air. Actual work of conditioning is handled locally, usually on each floor of a multi-story building. At each such point there is a "fan room," containing fresh-air intake, filters, washers, coils, etc. Each such fan room supplies a duct system for its own floor, with the usual supplies and returns.

While the local conditioning equipment may be assembled for the individual job, it is also common practice to employ packaged assemblies like Fig. 8, 9. Each such unit acts as a separate air-distribution center for its own area. The packaged assemblies greatly simplify installation and reduce cost. Unit of Fig. 8, designed to hang from the ceiling, contains filters, a direct-expansion coil, spray nozzles for humidification, a reheating coil and a fan. Similar models use chilled water for cooling. Unit of Fig. 9 fits smaller jobs and is designed for an exposed location where appearance may be important. It may also be obtained with cooling coils designed for either refrigerant or chilled water.

**Room Conditioners.** Unit of Fig. 9 might properly be called a "room" conditioner. But we apply the term here to equipment in which the refrigerating elements are closely associated with the others and which are suitable for use in relatively small spaces, such as individual offices, hotel rooms, etc. There are two broad types of room conditioners — floor and window models. Many floor models have all the equipment inside the conditioned room, Fig. 11. Refrigeration condenser is usually air cooled — in this case by a short duct taking outside air through the window opening. Only about 6 in. of window height is needed for this.

Some floor models, Fig. 12, have refrigeration equipment outside the unit itself, in a nearby closet, for example. If this can be done, it tends to yield quieter operation. Since there is no flow of condenser air through the unit itself, any moisture condensed on the cooling coils must be carried off in a drain. It is customary to locate such a conditioning unit near a window so it can be used for ventilation by drawing in fresh air from outside.

Window models, like Fig. 13, are usually complete unit air conditioners designed for mounting in a window opening. The low side, consisting of an evaporating coil, circulating fan and filter, usually is on the room side of the window line. The high side — compressor, condenser, and its cooling fan, extend outside. This simplifies the air cooling of the refrigeration equipment. Such units are extremely easy to install, requiring only electrical connections.

**Reversed Operation.** Room conditioners with the refrigeration equipment inside the room may be used to provide some heating in winter months. The cooling coil becomes the condenser and the condenser acts as an evaporator. This is, in effect, the basic principle of the heat pump. Operated in this way, the unit abstracts heat from the outside air and delivers it, at a higher level, to the room. Outside air temperature has to be at least 45 F for satisfactory reversed-cycle operation of this kind.

As the name implies, room conditioners are primarily intended to serve a single, relatively small space. Hence they usually discharge directly into the space, without ductwork for air distribution. Some room air is mixed with outside air; usually a damper arrangement is provided for control.

**System Selection.** As the foregoing pages indicate, there are many answers to the individual problems of different types of buildings. Much depends, of course, on the size and type of building and whether it is to be air conditioned throughout. For small buildings, and for conditioning of isolated spaces in large buildings, room or unit conditioners may prove the answer. In larger buildings, where a complete job is involved, much depends on whether conditioning equipment must be fitted into an existing building. With a completely new building considerable freedom of choice is possible.

In existing buildings, the problem of finding space for ductwork may prove tl vital factor. Lack of space points to use of a high-velocity conduit system or to the circulation of chilled water with local fan rooms serving individual spaces. In high buildings, the duct problem is likely to be acute, and so the alternatives prove attractive. If vertical zoning is used, with a fan room on each floor (a common scheme) care should be taken to seal off each floor from the others. If this isn't done, cool air tends to migrate to lower stories and warm air to upper.

Type of occupancy and amount of individual control required determines to a large extent (1) the degree of zoning on a horizontal basis and (2) the most suitable of the several methods for controlling distribution to zones.

## ACKNOWLEDGMENTS

For preparation of this section, considerable general information and specific technical data were made available by manufacturers in the air-conditioning and allied-equipment fields. POWER wishes to acknowledge its debt to the following for their help and cooperation:

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# Lubricants

By J J O'CONNOR, Managing Editor

A simple shaft, turning in a plain bearing, brings into play a maze of lubrication theory and practice. In the hectic rush of their daily jobs, plant people may not always take the time to master this theory, get a good working knowledge of lubrication phenomena. But they should. The whole area of reducing friction and wear between moving surfaces is becoming increasingly important. As industry continues to expand, that growth is reflected in more shafts, turning at faster speeds, under greater loads and at higher temperatures.

As setting for our story of lubricants, we chose the microscopic cross section of a bearing and shaft sketched above. This is the physical framework within which the lubricant works – but with a host of variables.

How far surfaces are separated is the first variable. In the plant, many bearings spend a good part of their operating lives in close metal-to-metal contact. Others are kept well apart by a complete film of lubricant. But a multitude of applications fall in between these two extremes. So to really know lubricants you must understand the conditions which exist at bearing-shaft surfaces under thin and thick lubricating films, and precisely what determines whether the lubricant will form a thick or a thin film.

Next we tell the story of the additives that go to work in almost all lubricants, enhancing their properties so they do a better job under varying conditions. This matter of additives raises the biggest questions in the minds of plant people. What are additives? Where and how are they used? Do they really work? How long do they last? We try to answer these questions, and others.

Then we tackle the various types of lubricants used across industry. Mineral oils, synthetics, hydraulic fluids, greases and the fast-growing array of solid lubricants are all covered. Our aim is to give an overall state-of-the-art report, rather than simply concentrate on what's new.

You can put the information to work in many ways. Obviously, it will be that much easier to discuss specific problems and particular fluids with your oil supplier when you're both talking the same language. And with this broad background, you can better understand new lubricants as they come on the market. Finally, a continuing benefit will be better appreciation of the overall importance of wear reduction and the means at hand to do the job.

# Although a lubricant must meet many related requirements,

### Control friction

With moving surfaces fully separated by a fluid film, friction is due to shear within the lubricant. A heavy, viscous film generates more internal friction than a light one, and energy expended to overcome friction converts to heat. As film thickness is reduced, with some metal-to-metal contact, chemistry of fluid and reactions at mating surfaces gain importance.

### Reduce wear

We mean wear from metal-to-metal contact and abrasion traced to solid particles coming between lubricated surfaces. Abrasion shows up as scratching or scoring; it's eased by flushing action of lubricant. Metal-to-metal contact and consequent wear happen if normally well-separated surfaces start to move or slow down, or if fluid-film thickness or body is reduced.

### Reduce corrosion

For indoor equipment operating in low humidity, corrosion control may be simple in absence of corrosive materials. Where acids, caustics or other corrosives are present, a constant resupply of lubricant may be required, plus means for mechanically limiting contamination. Excess acids, alkalies, even water alone may destroy the basic structure of many greases.

### Limit temperature

Lubricated surfaces must rid themselves of frictional heat by radiation or conduction through solids to cooler surfaces; or the lubricant may transfer heat to cooler zones. Lubricant controls temperature by first minimizing friction, then carrying off heat. How well this job is done depends on quantity of lubricant, temperatures, means for external cooling.

### Dampen shock

Shock loading must be considered in many mechanisms, such as gears. One saving grace is the inherent ability of fluid lubricants to increase their viscosity as pressure increases. A typical oil refined from a California crude ups viscosity 100 times as applied pressure rises from atmospheric to about 25,000 psi — not an uncommon order of magnitude.

### Form a seal

Greases are often used where lubricant retention is a problem. Since they have a built-in ability to seal the shaft in a bearing housing, greases serve to keep themselves *in* the bearing and contaminants *out*. An over-supply of oil on a once-through basis also has a sealing action: Case-in-point is the lubrication of cylinder walls in an internal-combustion engine.

# HOW LUBRICANTS WORK as thickness

Making moving parts slide or roll with greater ease is the obvious reason for using lubricants. If it were the only reason, we'd just have to worry about the job of separating surfaces with a fluid or slippery solid. But a host of additional requirements are placed upon today's lubricants apart from surface separation. Some are listed above.

Most of these added chores are interrelated. For example, a lubricant doing a relatively poor job of controlling friction must assume the added burden of removing more generated heat. This additional heat may thin out the fluid, which thus winds up as a poor lubricant for the job at hand. Result: an early end for both lubricant and bearing.

**A lubricant's "secondary" functions** should always be considered. That means tailoring the lubricant to suit its operating environment. How some of that tailoring is done is discussed on pp 8-9. Before scrutinizing the many lubricant types found across industry today, let us take a close look at the way lubricants work. As a logical starting point, why not first step back and examine a world without lubricants — a world of dry friction.

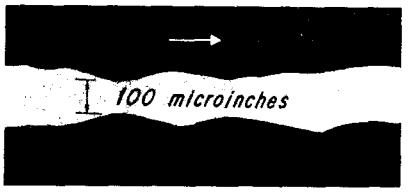
**Friction** is the force that resists sliding motion. The term *coefficient of friction* relates this friction force to the load: it's simply friction force divided by load.

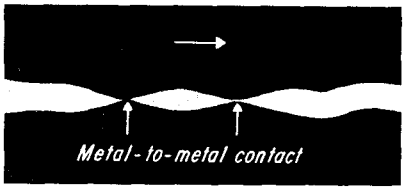
Two facts about friction will aid in understanding the mechanics of lubrication. First, friction force is independent of apparent contact area, so large and small areas of contact, if they're made of the same materials and support the same weight, will have the same coefficient of friction. Second, friction value hinges on the shear resistance of surface materials, as discussed further below. For most practical purposes, it is independent of sliding velocity except under starting conditions, which simply means that friction force to be overcome before the body can start sliding is greater than needed to keep the body moving.

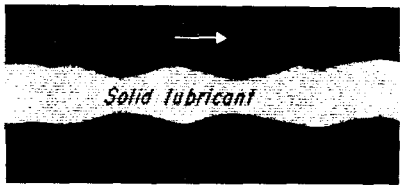
**What causes surface friction?** To understand this, accept the fact that even finely finished surfaces are made up of hills and valleys — you can see them when you look through a microscope. When surfaces contact in the absence of a lubricant, high spots or *asperities* on one side meet hills on the other. When load is at rest, these points will flatten and cold weld. So with dry machined surfaces, major frictional force comes in shearing welded points.

What about rolling friction, as in ball bearings? Any system of rolling elements reduces friction considerably. If balls and opposing flat surfaces were completely smooth and inelastic, friction would be essentially zero. But ma-

# its prime function is to separate moving loaded surfaces




## Full film

A bearing's "smooth" finish is far from smooth when looked at closely. Above sketch of a magnified oil gap between shaft and bearing shows up typical contours. Full-film condition illustrated —a goal often aimed at, not always realized — is termed *hydrodynamic lubrication*. Here separation of surface high points (asperities) most likely to contact is represented as 50-100 microinches; that's about the thinnest oil film you can have and still consider it full-fluid hydrodynamic lubrication.

Pressure is the key to separating surfaces. In hydrodynamics, pressure buildup comes from within the bearing. In hydrostatics, pressure comes from an outside pumped source. Hydrostatic technique is used for slow, heavy loads or to cut down starting friction by lifting journal off the bearing surface.

## Mixed film

When film thickness shrinks for one of many reasons and metals contact, asperities become the real load carriers. Since this true load-bearing area is small stacked alongside the total bearing surface, you can expect the unit pressures to be high. Called *semi-fluid* or *mixed-film lubrication*, this part fluid, part metal-to-metal-contact condition is found widely in industry. It varies from boundary lubrication (discussed in text below) only in degree. Here, friction is influenced by surface material and composition of lubricant. Often but a single molecular layer of lubricant plates the surfaces. This film resists penetration, but with middling success. Even under best conditions — good adsorption, close molecular packing on clean surfaces — some asperities penetrate the monolayer.

## Solid film

A solid lubricant is a solid material placed between two moving surfaces to reduce or prevent metal-to-metal contact. It may be one of the well-known laminar solids such as graphite or molybdenum disulfide in one of many forms; or a material added to mineral oils, synthetic fluids or greases. Even natural oxides found on metal surfaces are a form of solid lubricant. Plastics have made a mark. Bonded coatings of solid lubricants are seeking out increasing applications.

If pure hydrodynamic lubrication could always be established and maintained there would be little need for solid films. But this is not the case. In most practical applications, bearing surfaces do sometimes meet in actual rubbing contact, so lubrication often must include some low-friction solids.

# varies from a single layer to a full film

terials deform and rolling elements slip under load, bringing to bear the principles of sliding friction.

When a lubricant is introduced, its immediate effect is to reduce the coefficient of friction — to let the sliding surfaces move with less effort expended.

Even a dry surface may have some form of natural lubrication: absorbed gases, water vapor, oxide films, surface contaminants. Although far from satisfactory lubricants, they do help reduce friction. At the other end of the scale is *hydrodynamic lubrication* (see sketch above), where a full film of oil supports load. But before we go into that, let's look at the area in between, called *boundary lubrication*. Here, as in the mixed-film area, the lubricating film is thin and some metal-to-metal contact occurs.

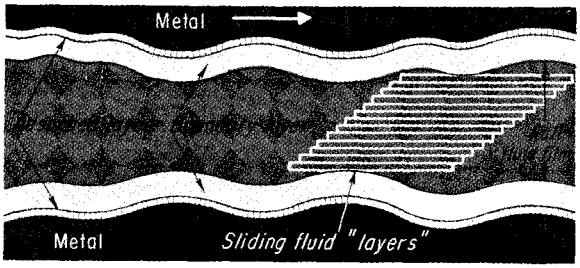
**Boundary lubrication** — a situation that's not ideal but one common to most moving surfaces — is a step or two below hydrodynamic, but a big step above dry friction. Practical boundary lubricants reduce coefficient of friction for cleaned steel from about 0.5 to the range between 0.2 and 0.03.

In denuded metal, the high surface energy encourages welding at points of real contact. Here's where a thin protective layer comes in, suppressing this surface energy and keeping high points physically separated. Often this thin film is provided by an additive.

**Physical adsorption** of molecules plays a key role in boundary lubrication. Lubricant molecules, plated out as a single or monolayer on the bearing surfaces, aid in reducing friction. Although nonpolar fluids are sometimes used in lubricants, polar type molecules are the most practical. They have a self-orienting feature which lines them up on metal surfaces, standing on end with their bottoms attached to the metal like barnacles (p 5). This, plus close shoulder-to-shoulder packing, accounts for their ability to inhibit metal-to-metal contact. Stearic acid is typical of the fatty-acid molecules used as polar additives.

But molecules will detach as well as attach. As temperature increases, physical vibrations of molecules tend to increase, resulting in some polar molecules dropping off. (When temperature drops, of course, there is a tendency for molecules to adsorb again.) Heat developed by plastic and elastic deformation of the metal, plus fluid shearing, tends to destroy the adsorbed film. That's why, in facing up to boundary lubrication, it's necessary to continually furnish a fresh supply of molecules for adsorption.

Some researchers believe effective boundary lubrication




## Understanding the fluid film: how it shears, builds pressure

The sketch above makes a number of assumptions for the sake of getting ideas across, assumptions which wouldn't hold up under rigorous examination. It assumes that oil flow in a full-film bearing is always laminar (layer-like). This is usually the case but there are exceptions. The sketch shows a clear-cut line between boundary and full film, which isn't there. But our sketch and the following text, in combination, show some of the fundamentals of how a film shears, how hydrodynamic film pressure builds.

Look upon a fluid film as a deck of cards with the top card adhering to the moving shaft, bottom card anchored to the bearing. In motion, the deck splits in layer-like fashion. It's this sliding of layer upon layer that accounts for the fluid's internal friction. Layers of heavy, high-viscosity oil are tough to slide by one another. But light, low-viscosity fluid behaves like a highly waxed deck; laminar sliding is just that much easier.

Building our deck of cards into a working hydrodynamic oil film involves a series of factors: clearance, bearing grooving, point of oil application, speed, load, and of course viscosity of the lubricant. But the mechanics of film formation are quite straightforward.

As the journal starts turning, it literally rolls uphill on the bearing surface. And since the journal is then slightly off center, the clearance becomes crescent-shaped, with the wedge end of the crescent tucked into the load area (top journal sketch, facing page). As speed increases, oil is dragged from the crescent to form a thin oil film in the bearing-load area. Since the shaft and bearing converge, in effect, oil will leave the high-load area at a higher average velocity than it had when it entered. So there is some tendency for the fluid to back up in the wedge-shaped load area. And since oil cannot be squeezed into a smaller volume, its pressure builds up instead to support journal load.

can be attributed only to the first molecular layer plating the metal: outer layers, being weakly held, are squeezed out as load increases. But other experts believe that more than a monolayer is needed for reasonably smooth sliding.

Molecular weight and chain length of the adsorbed polar molecules enter the picture. Coefficients of friction — static and kinetic — decrease as molecular weights increase. And because of the relatively low cohesive force between adjacent short-chain polar molecules, they lack much in effective lubrication ability.

**End result** is that quantity of physically adsorbed molecules, and hence lubrication effectiveness, decreases as temperature and physical activity increase. So boundary lubrication utilizing physical adsorption should be limited to low loads, low sliding speeds, low temperatures (a few hundred degrees F).

**Chemical adsorption** (chemisorption) is another approach through additives to providing a plating layer in the thin-film region: forming a surface film by chemical action on load-bearing metal. In contrast to physical adsorption, chemisorption increases with temperature. Metals more readily attacked chemically are usually more effectively lubricated by chemisorption. Example: Fatty acids do a good job on iron and copper, a poor one on chromium and silver. Chemically adsorbed films work well right up to their melting point.

**Chemical reaction** is still another way to form a low-friction coating on metal surfaces. It occurs when there is an exchange of valence electrons, so a truly new chemical compound is formed on bearing surface. Typical would be sulfur reacting with iron to form iron sulfide. Chemical reaction is a way to develop extreme-pressure (EP) lubricants. The approach works with high loads, temperatures, sliding speeds, but it's limited to reactive metals. Inorganic films formed (sulfides, chlorides, phosphides) appear more stable than any physically or chemically adsorbed film.

Developing a lubricant with extreme-pressure characteristics is a reasonably precise business: it should be tailored to each particular job so that temperature, pressure, sliding speed, metal combinations are known. There are a few precautions to keep in mind. For instance, although sulfur is adsorbed rapidly on copper as is phosphorus on ferrous alloys, chlorine used with lead may *increase* friction.

Ever see an old-timer slip sulfur into a gear-case lubricant during wear-in? Elemental sulfur dissolved in oil has been used for years as a chemically reactive additive. Moderately high concentrations of sulfur in oil yield the highest load-carrying capacity of any blend that must face up to extreme-pressure conditions. But you can pay a price: some harmful effects on the oil and the metals, possibly an increase in wear rate with time.

**Other materials** such as chlorine, bromine and iodine (or compounds containing these elements, see pp 8-9) react chemically with metals to form salts with a resultant protective layer. Petroleum oils fortified for extreme pressure may contain sulfur and chlorine, sulfur and phosphorus, sulfur plus phosphorus and zinc or others.

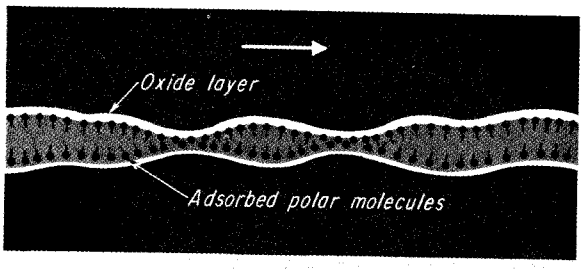
There are many more chemical reactions that may occur on a load-bearing surface using a hydrocarbon boundary lubricant: surface oxidation, hydrocarbon oxidation forming acids, polymerization of hydrocarbons to yield resinous films, oxidation, hydrolysis or interaction of additives.

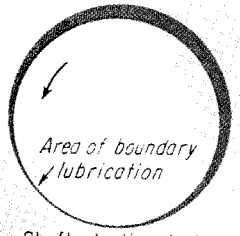
## Adsorbed lubricant monolayer helps support load on startup

On startup, unit pressures at high spots in contact may be 40 times those calculated for the total projected bearing area. This accounts for fact that even with modest bearing loads, actual loading in areas of solid contact may reach yield point of bearing material.

Transition from contacting asperities through monolayer support to thick film is gradual. How quickly this transition is made — if ever — depends on viscosity, journal speed, bearing loading.

Both the boundary and mixed-film regions on curve (right) are areas where a solid lubricant, one of the many types available, might be used as part of a fluid lubricant. Mineral oils of low refinement have a natural advantage in the mixed-film area. This comes about because of built-in polar materials (see p 3) which are removed by high refining. Of course they can be put back in another form after refining, and they often are.



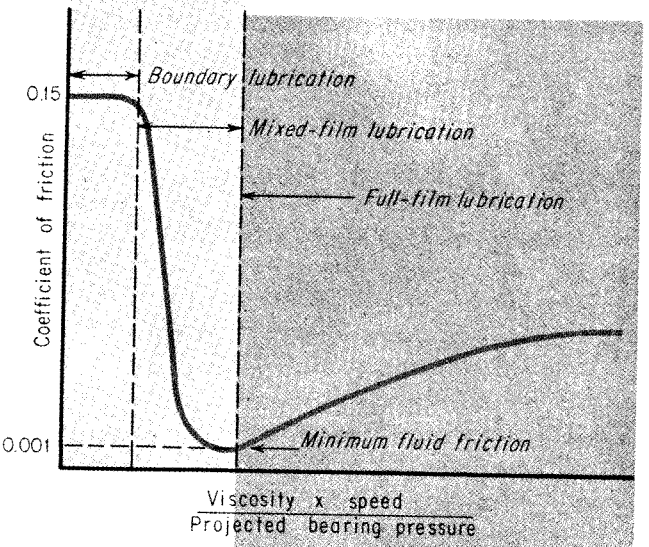




Shaft starting to turn

Shaft and bearing contact through touching asperities gradually gives way as speed increases, film pressure builds up. Lubrication shifts from boundary to mixed-film to full-film

## Viscosity, speed, bearing load determine friction, film thickness

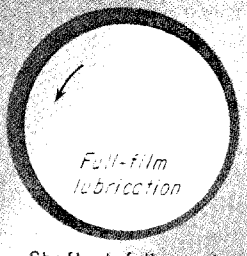
In selecting a lubricant, viscosity becomes the important factor once designer has fixed journal speed and bearing load — assuming we're aiming for the hydrodynamic full-film region. Viscosity — the fluid's internal resistance to motion — must be determined so it can handle maximum load without over-heating. Increasing viscosity permits more loading, but higher bearing temperatures may result from the normal increase in fluid friction. Since oil thins out (viscosity decreases) with rise in temperature, it's important to know the bearing's operating temperature and the true viscosity of the lubricant at that temperature. Viscosity shows its real importance in full-film lubrication. It is the single property that allows oil to resist being squeezed out as load is applied. Actually, increasing pressure on a fluid lubricant tends to increase viscosity, one reason why low-viscosity oils can handle heavy loads.



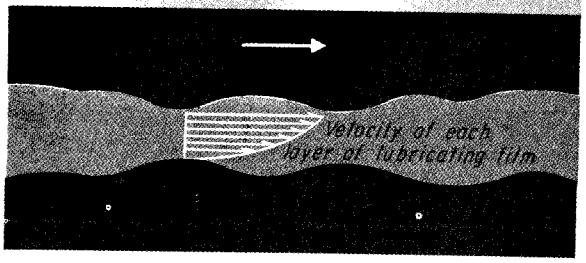

## Hydrodynamic pressure within fluid keeps surfaces separated

Once in the full-film region, many machines shift bearing loads in both size and direction. An example is the internal-combustion engine, where loading is anything but constant. This holds especially true in the connecting-rod bearings, main-crankshaft bearings, camshaft bearings, piston-ring bushings. Reciprocating pumps and compressors have similar shifting loads. When bearing load increases or changes direction, the shaft will generally shift its position until all forces are again in equilibrium. This radial motion means part of the oil film will be squeezed and forced to flow around the shaft. But because of its viscosity, the oil pushes back against this change in shaft position, somewhat akin to fluid in a hydraulic-damping system. This resistance and resulting squeeze film actually add to the oil film's load-supporting ability.

Pressure developed by spinning shaft, dragging oil into wedge-shaped layer between journal and bearing, clearly separates surfaces. Only friction is due to viscosity of fluid




Shaft at full speed



# KEY PROPERTIES of fluid lubricants and

Common practice, in writing about lubricants and their properties, is to simply list the most important ones and possibly describe the means available for testing. These listings have some value to the user because they describe the product. They also help him, in a preliminary fashion, screen suitability of a proposed lubricant for a given job.

The ultimate check on whether a specific lubricant is suitable for the job at hand would be an on-site performance test. But such a test is seldom feasible because it's costly and time-consuming. Also, there is the problem of controlling and duplicating widely varied operating conditions met in full machine range.

If field testing were the only answer, progress in lubricant development and machine design would be throttled. The compromise, of course, is *simulated* performance testing, carried out in laboratories of major oil suppliers.

After performance is proved, some yardsticks are needed to help maintain the lubricant's quality and serve as an aid in purchasing. It is at this point that a lubricant's chemical and physical properties really come into the act.

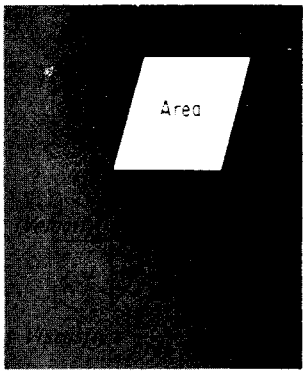
**List of properties** would start off with viscosity, then viscosity index, pour point, gravity, flash and fire points, neutralization number, oxidation stability. You can continue on to any length dictated by the product's ultimate use. The most complete and authoritative source of details on how to conduct tests on a lubricant is the *ASTM Standards on Petroleum Products and Lubricants*, issued annually. It is available from ASTM, 1916 Race St, Philadelphia 3, Pa.

Now let's look into the more important properties of lubricants. Our logical starting point is viscosity.

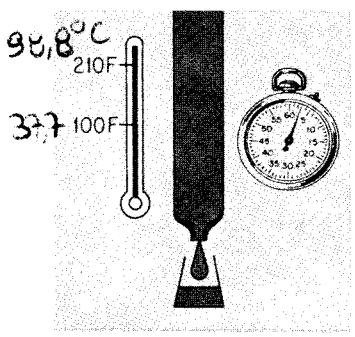
**Viscosity** has been accurately described as the internal resistance offered as one portion or layer of a liquid moves in relation to another portion. Resistance comes about because of the internal friction of the liquid molecules moving past each other. Since temperature is a measure of molecular activity, it is the most important variable affecting a liquid's viscosity. For that reason, temperature must always be stated in conjunction with viscosity.

Probably the best way to understand viscosity is by starting out to measure it. Sir Isaac Newton is credited with being the first to set up a formula for the force needed to overcome viscous resistance of a fluid. Even though he did this work back in the early part of the 18th Century, it was done so well that the relationships he established are still used as the basis for viscosity measurement.

## How viscosity is measured . . .




**ABSOLUTE VISCOSITY** (see sketch) can be measured several ways. One way uses the time required for a steel ball to fall through a measured height of oil. The equation is $\mu = K(D_b - D_l)t$. $u$ is viscosity, $D_b$ density of ball, $D_l$ density of liquid; $K$ is a constant peculiar to the instrument; $t$ is measured time for ball to pass two horizontal markings on a glass tube. For example: time for a 0.15-cm-dia ball to fall 15 cm through a 2-cm-dia tube of castor oil at 68 F is 19.4 sec. This is a fine method for measuring viscosities of 1000 centipoises or greater.

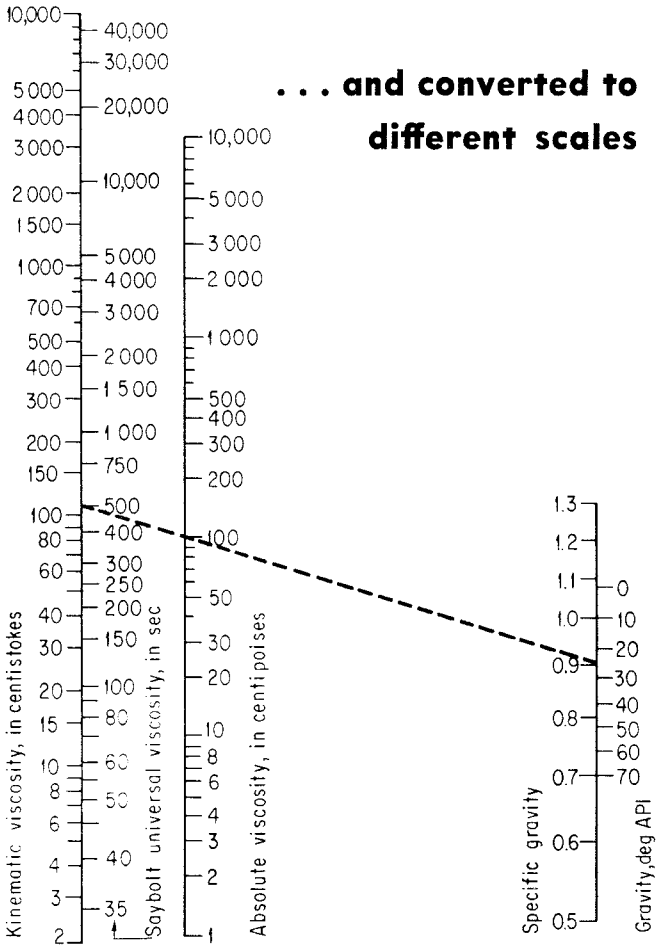



**KINEMATIC VISCOSITY** is more widely measured than absolute. This is the ratio of absolute viscosity to density of the oil at a given temperature.

In the U.S., Saybolt Universal Viscometer values are the ones most widely quoted as a measure of viscosity. Instrument (shown simplified at left) consists of a cylinder to hold oil sample plus a short, small-diameter-outlet tube closed by a cork stopper. A constant-temperature bath surrounds cylinder. You note how many seconds it takes for 60 cc of the oil to flow into a flask: this is the viscosity measured in Saybolt Seconds Universal (ssu).

100F

## . . . and converted to different scales




**ABSOLUTE VISCOSITY** of sample is 100, specific gravity 0.9. To find Saybolt, connect 0.9 sp gr with 100 cp, read 500 sec on ssu

# why they are important

Newton used two long concentric cylinders submerged in water for his fundamental testing, but the same principle holds for the technique sketched at left (alongside the discussion of absolute viscosity). Here two surfaces are, in effect, separated by a fluid film. The basic equation $\mu = FH/AV$ defines viscosity, $\mu$. $F$ is in lb, dynes, etc, area $A$ is distance squared, height $H$ is distance and velocity $V$ is distance divided by time; viscosity then has the dimensions of force multiplied by time and divided by distance squared.

If we're using the English system of units, we find dimensions in lb-sec per sq in. This unit is labeled the *Reyn*. In the European or metric system, viscosity would be dyne-sec per sq centimeter. This unit is called the *Poise*. A Poise is a rather large unit, so the *centipoise* (1/100 of a Poise) is frequently used instead. When converting from one to another, remember that the number of Reyns equals $1.45 \div 10^7 \times$ number of centipoises.

Newton further deduced that the viscosity of a given liquid is constant at any particular temperature and pressure, and independent of the rate of shear within the fluid. Fluids obeying these laws are labeled *Newtonian*. However, viscosities of greases and polymer-thickened mineral oils are affected by shearing; these are termed *non-Newtonian*.

Other properties range far and wide, depending on requirements the intended service places upon the lubricant.

**Viscosity index,** discussed more fully at right, is certainly a key property since it indicates how viscosity will change as a function of temperature.

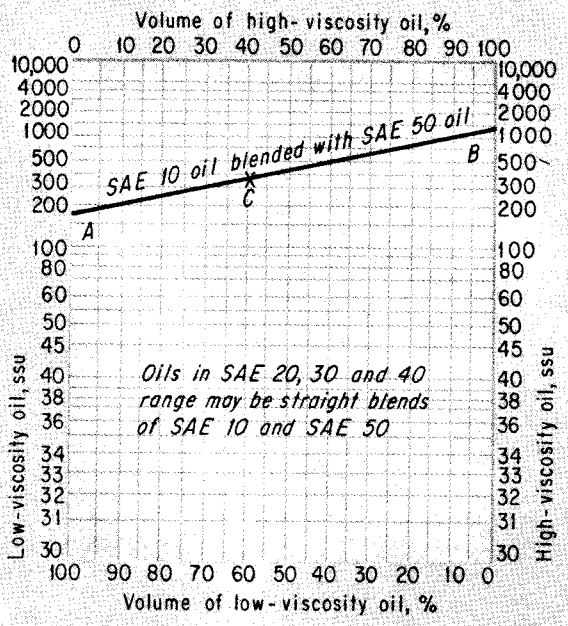
**Pour point** relates to viscosity, too, since it concerns fluidity at low temperatures: it is the temperature at which an oil just barely flows, under certain prescribed conditions. Of course, refrigeration oils and lubricants intended for cold climates must have low pour points.

**Flash point** is the temperature to which a lubricant must be heated before its vapor, when mixed with air, will ignite but not continue to burn. At its *fire point*, lubricant will keep on burning. High flash points and high fire points have an obvious plant-safety value.

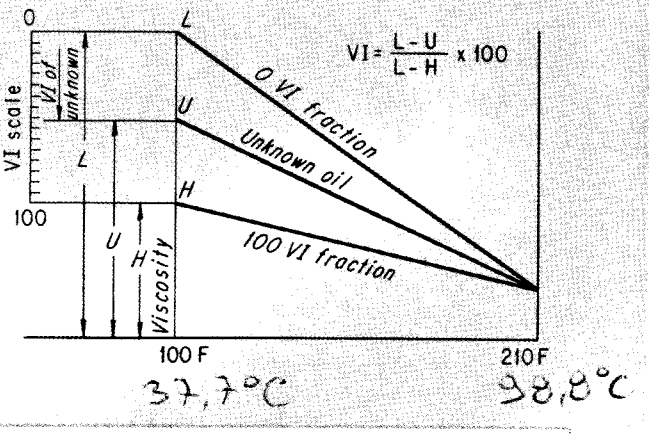
**Acid content** is an important gage of the life of used oils. Oils oxidize with age and service, forming acids which lower the surface tension. *Interfacial tension* is one check on acid content. Another is *neutralization number*, expressed as milligrams of potassium hydroxide required to neutralize one gram of oil. Both are often used to tell when circulating oils need changing.

The above are but a few of the more commonly discussed properties. Actually, it is quite possible to divide the important functional properties of a lubricant into six main groups. Any such grouping would lead off with *flow properties*—viscosity, VI and low-temperature suitability. Next might come *high-temperature characteristics*, centering around volatility, evaporation residue, thermal stability, decomposition products and residues. Then *oxidation characteristics* would include inhibitor susceptibility, resistance to oxidation. *Hydrolysis* would cover resistance to alkaline liquids, acids, water or steam. Finally we'd want to know *solubility* in water, in hydrocarbon solvents, miscibility (how well it mixes) with petroleum products.

## How oil is blended




**TO USE CHART,** draw a line through points *A* and *B*, representing viscosity at 100 F of oils to be blended. Proportions of each are read off the top and bottom scales. Example shown is for a final blend of 350 ssu at 100 F. Such an oil, point *C*, requires 60% 175-ssu oil blended with 40% 1300-ssu oil. Similar chart determines fuel dilution.




## Story of viscosity index

Since viscosity of fluid lubricants does change with temperature, a measurement of how much change occurs has been set up and labeled the *viscosity index*. Present system compares viscosity measurements from two crude oils. The two selected were believed to possess the absolute maximum and minimum limits of viscosity-temperature sensitivity. As such, they were assigned VI's of 0 and 100 as the end points of a 100-point VI scale.

But since the time these crudes were selected, newer developments—advent of solvent refining, modern additives and the growing number of synthetics—have complicated matters. We now have a string of lubricants ranging far outside the VI scale in both directions. Many are considering a new index, or probably two, one for commercial use and a more fundamental scale for research.

## Commonly used additives for today's industrial lubricants:

| Additive type | Oxidation inhibitor | Corrosion inhibitor | Extreme pressure, oiliness or film-strength improver | Detergent-dispersant | Rust preventive |
|---|---|---|---|---|---|
| Typical compounds | Organics containing sulfur, phosphorus or nitrogen, such as organic amines, sulfides, hydroxy sulfides, phenols. Zinc organics are often used | Organics containing active sulfur, phosphorus or nitrogen. Typical: organic sulfides, phosphites, metal salts of thiophosphoric acid and sulfurized waxes | Chlorine, phosphorus and sulfur compounds such as chlorinated waxes, organic phosphates (tricresyl phosphate), phosphites, lead soaps such as lead napthenate, fats | Metallo - organics (phosphates, phenolates, sulfonates and alcoholates). High-molecular - weight soaps containing tin, barium, magnesium, calcium | Sulfonates, amines, fatty oils, fatty acids, oxidized-wax acids, phosphates, halogenated derivatives of some fatty acids |
| Why additive is used | Minimize formation of varnish and sludge on metal parts, prevent corrosion of alloy bearings | Protect alloy bearings and other metal surfaces from corrosion | Reduce friction and wear, prevent galling, scoring and seizure | Keep metal surfaces clean, prevent many types of deposits | Minimize rusting of metal parts during equipment shutdown, storage and shipment |
| How additive works | Reduces formation of acidic bodies by decreasing amount of oxygen taken up by the oil. Ends oil-oxidation reactions by forming inactive soluble compounds or by taking up oxygen. Additive may be oxidized instead of oil | Inhibits oxidation, preventing formation of acidic bodies. Allows a protective film to form on metal surfaces. Catalytic oxidation of oil is decreased by this chemical film | Chemical reaction forms a film on contacting metal surfaces. Film has lower shear strength than base metal, thereby reducing friction. Helps prevent welding, seizure of contacting surfaces when oil film is ruptured | Chemical reaction prevents deposition of oxidation products and other substances | Polar or chemical type surface-active materials are preferentially adsorbed on metal. Film repels water attack |
| **Typical lubricant applications and additive that may be used** | | | | | |
| Turbines, electric motors, spindles, hydraulic and circulating systems | ✓ | | ✓ | | ✓ |
| Air compressors | ✓ | | ✓ | | ✓ |
| Gears (hypoid, heavy-duty, worm | | | ✓ | | ✓ |
| I-c engines | ✓ | ✓ | ✓ | ✓ | ✓ |
| Soluble EP oils | | | ✓ | | ✓ |
| Fire-resistant non-aqueous hydraulic fluids | ✓ | | ✓ | | ✓ |
| Ball- and roller-bearing greases | ✓ | | ✓ | | ✓ |

# ADDITIVES improve lubricant properties, create some new ones

Today's petroleum lubricants have arrived at their high stage of development for two reasons: modern refinery techniques plus the contribution made by additives. It's clear that the biggest stride in lubricant development over the past decade has been in the science of improving properties or creating new ones through additives.

**Adding something** to lubricants is an old art. Steam-cylinder oils compounded with animal fats and the marine-steam-engine lubricant that boasted of blown rape-seed oil were among the first additive lubricants.

Ever-growing trend toward transferring more energy through small mechanical packages, problems brought about by fuel impurities, higher bearing and gear loadings, greater speeds, widening range of operating temperatures . . . all these and more are behind the growing field of additives. And this area will continue to expand.

**How do additives improve the lubricant?** That calls for a 4-part answer. First, there are additives designed to

# What they are, how they work, typical lubricants using them

| Metal deactivator | Antiseptic (bactericide or disinfectant) | Pour-point depressant | Emulsifier | Foam inhibitor | Viscosity-index improver |
|---|---|---|---|---|---|
| Complex organic compounds containing nitrogen or sulfur: amines and sulfides, lime soaps | Some alcohols, aldehydes, phenols and mercuric compounds. Chlorine - containing compounds | Wax alkylated naphthalenes or phenols and their polymers. Methacrylate polymers are also used | Certain soaps of fats and fatty acids, sulfonic acids or naphthenic acids and surfactants | Silicone polymers and modified waxes | Polymerized olefins or iso-olefins. Butylene polymers, methacrylic - acid - ester polymers, alkylated styrene polymers |
| Form, prevent or counteract catalytic action of metals on oxidation process | Control odor, metal staining and emulsion breaking in emulsion type oils | Lower the pour point of the oil | To produce a coolant-lubricant type fluid from soluble oils and water. Reduces water washing, rusting | Prevent the formation of stable foam | Reduce rate - of - change of viscosity with temperature |
| Physical or chemical adsorption forms inert, protective film. Chemically inactive complex is formed with soluble or insoluble metal ions | Reduces or prevents microorganism growth particularly harmful to emulsified oils | Coats wax crystals in oil to prevent growth and interlacing at reduced operating temperatures | Surface-active chemical agents reduce interfacial tensions so oil can be finely dispersed in water | Reduces interfacial tension, allowing small bubbles to combine into larger air pockets. Latter will separate faster | Improvers are less affected by temperature change than is oil. Example: They raise viscosity by a greater proportion at 200 F than they do at 100 F |
| ✓ | | ✓ | | ✓ | |
| | | ✓ | | ✓ | |
| | | | | ✓ | |
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| | ✓ | | ✓ | ✓ | |
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| ✓ | | | | | |

protect the lubricant in service by limiting chemical change or deterioration. Second, there are additives which protect machines from effects of outside contaminants such as products of combustion, which might end up as lubricant deposits. Third, some additives improve a lubricant's physical properties (pour point, VI, etc) or give completely new properties. Fourth, others reduce surface wear.

**Additive properties** are important too. Additives must often be soluble in the base petroleum product. In most cases, this solubility must be maintained over the whole in-service temperature range. But there are exceptions: VI improvers, for one, may depend on limited solubility since their action varies with temperature. Rust inhibitors could be troublesome if solubility were fully stable, since this would block their concentration on metal surfaces. Solubility in oil rather than water is important. Otherwise water finding its way into a gearcase would tend to leach out water-soluble additives.

Volatility must be low so additives in the finished product won't be lost once temperatures rise. Compatibility, stability, odor, color, controlled activity all have an effect.

**False concept** in connection with additives concerns the quantity to use. You might automatically conclude that the bigger the amount, the better the results. Actually, the contrary may be true. For example, some EP agents have a bad effect on properties such as demulsibility, stability, surface tension. Final decision on quantity and type of additive is best left to the lubricant supplier.

# MINERAL OILS

Lubricants may be broadly classified as gas, liquid, semi-solid or solid. Mineral oils produced from hydrocarbon crude are still the largest single class in common use.

**Crude oil** as it comes from the ground displays a wide range of properties. No two crudes are exactly alike; even crudes from wells in the same field may have differing characteristics if the wells tap into two or more horizontal strata. Although alike in basic content, crudes are actually an extremely complex mixture of hydrocarbons. They vary in color, odor, density, viscosity, chemical composition.

Some crudes are light enough to be used as diesel fuel. Others have a tar-like consistency and even in the tropics must be heated for pipeline transmission. But there is a common denominator: all crudes contain carbon and hydrogen plus small amounts of sulfur, oxygen, nitrogen. Carbon content runs between 83-87%, hydrogen 11-14%.

**Classification of crudes** is usually according to the composition of the residual fractions left after refining: paraffinic, napthenic and intermediate or mixed-base. Paraffinic-base crudes such as the Pennsylvania oils boast the highest natural viscosity index; napthenic crudes have lower values. And there are other basic differences: pour point, carbon residue, flash point and volatility, to mention but a few. However, many differences in the crudes can be offset by modern refining and use of additives.

**Fixed oils,** from animals and vegetables, are rarely used alone as lubricants since they tend to oxidize into a varnish-like layer at temperatures where mineral oils remain stable. So the fixed oils are generally combined with mineral oils and greases. Serving as oiliness agents, they're valuable in the boundary-lubrication region.

These oils get the umbrella label *fixed* because they cannot be distilled without decomposing. The family includes animal products such as tallow, lard, degras, and neat's-foot, whale, porpoise, dolphin oils. Vegetable oils, from seeds or fruits of plants and trees, are extracted by pressing or by chemical solvents. Among vegetable oils are castor, rape, cottonseed, olive, coconut, palm, peanut and rosin.

**Super refining** is showing much promise in mineral-oil development. Although emphasis over the past decade has been on additives to extend the usefulness of mineral oils and greases, possibility of further improvements in the refining process has not been overlooked.

Some researchers are taking a close look at super refining for petroleum oils. They aim to improve still further the viscosity-temperature and viscosity-volatility relationships, additive response and low-temperature flow.

Results to date with hydrocarbon fluids show a liquid range extending from −75 to over 700 F, with good thermal stability to 700 F, improved lubricity and response to additives that inhibit foaming, oxidation, corrosion and wear. Formulations based on deep-dewaxed super-refined mineral oils appear well suited for high-temperature hydraulic fluids, gas-turbine lubricants, instrument oils.

# SYNTHETICS

Widening interest in the synthetics as lubricants has come about simply because industry's needs are, in many areas, outstripping the normal limits for petroleum oils. And we can expect this interest to grow. One practical way to classify synthetics is by their distinguishing chemical source (see facing page). Properties of most synthetics can be improved through use of the same additives now serving petroleum products, and many new additives are being tailored solely for the synthetic family.

**Silicones** have the most favorable viscosity-temperature characteristics of present-day synthetics in general use. Available in a wide viscosity range (from 35 ssu at 100 F to semi-liquid greases), they boast low volatility, high thermal and oxidation resistance. They won't harm plastics, synthetic or natural rubbers. On the other side of the coin, their lubricity may fall short — but is improving, through structural change with halogens, additives containing tin.

The silicones find increasing use in rolling-contact bearings at temperatures to 350 F and in many applications where viscosity change with temperature must stay at a minimum. In grease form, they are particularly useful in hot-liquid pumps and in corrosive atmospheres.

**Polyglycols** are available in many viscosity and molecular-weight grades with viscosity-temperature characteristics better than petroleum, not up to silicones. Not only is cost low, but they can be substituted for petroleum lubricants without extensive design or material changes in the machine. Principle uses are in water-based fire-resistant fluids, rubber-molding lubricants, hydraulic-brake fluids, vacuum-pump and high-temperature lubricants. The polyglycols have a unique property: they decompose or oxidize into soluble fluids or volatile products, rather than sludge or varnish. But they attack paint and other nonmetallics.

**Phosphate esters,** a broad class of fluids, are used as fire-resistant hydraulic and air-compressor fluids, seriously considered for lubrication of steam-turbine-generators. Although they are strong solvents for paints and many rubbers, they are compatible with butyl and some of the silicone rubbers, nylon, Teflon, polyethylene.

**Dibasic-acid esters** are promising synthetics, widely used as base liquids for low-volatility greases: largest area is as aircraft-turbine lubricants. Many of these synthetics are made from animal or vegetable oils as raw materials, others from petroleum-hydrocarbon synthesis.

**Other fluids** include the silanes, the diphenyl ethers, sodium-potassium eutectics and numerous inorganic polymers of boron, phosphorus and nitrogen. These lubricants are being explored for use above 600 F.

**Applications for synthetics** are cropping up every day. Where extremes in operation are encountered, where fire-resistance is important, where equipment must operate for long periods unattended . . . these are areas where the man-made lubricants fit in. In light of the benefits they can offer when properly applied, their added initial cost can often be justified by long-term economic evaluation.

## What you can expect from mineral oils and their additives in service

If lubricant and additive are applied within design limits you have every right to expect that they'll hold up rather well. But every oil changes somewhat while it's on the job, usually in two ways: (1) internal or chemical change within the lubricant (2) change traceable to outside factors such as contaminants. These have an interrelated effect on lubricant life.

**Internal change,** notably oxidation, is common in mineral oils exposed to air, especially at high temperatures. Changed oil properties are to be expected once oxidation gets under way. Oil becomes corrosive toward some metals. Viscosity and neutralization number increase, color darkens. Later, insolubles form and deposit. Rate of this reaction depends on time, catalysts (such as water, metals), aeration, type of oil, service temperature. Oxidation rate is modest for, say, steam-turbine lubricants which operate at 130-140 F, in contrast to i-c crankcase oils which may run over 250 F.

**Complete oxidation reaction** is quite complex. Briefly, unstable *oxy* materials labeled *hydroperoxides* form when oxygen and hydrocarbon join. These oxy materials start decomposing, meanwhile regenerating, in a sort of chain reaction, additional material that is even more susceptible to oxidation. You can expect oxidation rate to double for each 18-F rise, go up even faster once some critical region is passed. Iron, copper and lead speed up oxidation to varying degrees.

Oxidation inhibitors are an immediate answer since they improve oil's stability, extend its useful life. But they tend to lose effectiveness after they've been in service for a time.

**Additives change, too.** Some have limited heat stability, especially after some use. At high temperatures they break down to form sludge and deposits. Here are other changes:

*VI improvers,* being high-molecular-weight compounds, tend to shear in close clearance — in a vane pump, for example. Result is a decrease in effectiveness with time.

*Rust inhibitors,* polar by nature, plate out on metal surfaces. Rate of additive depletion hinges on amount of water contamination, and how fast that water can be removed.

Other additives — detergents, film-strength improvers are typical — have a limited, though long, life span. This is a fact to keep in mind when scheduling oil-change periods.

**External factors** such as contaminants play an important role. The i-c engine is a case-in-point. Here the most troublesome contaminants are products of incomplete combustion, dirt drawn in with induction air, ash-forming material in fuel. If allowed to accumulate, these impurities increase wear rate, build up deposits in oil lines, ring grooves, piston skirts, crankcase, sump. Oil conditioning will help here.

Field problems point up other aspects of contamination. For example, a turbine oil seemed to show well-advanced oxidation when tested. Actually this was not the case. But another oil had been mixed in — a grade with a different neutralization number. Additives in the new oil reacted with the old oil, so neutralization-number titration yielded a higher value.

**Other contaminants** may be a primary cause of wear: flyash and coal dust are typical. Water can be a serious problem in turbine oils. It usually creeps in via leaky seals and oil-cooler coils or condensation from a humid atmosphere. Rust contamination can often be traced to poorly protected surfaces above oil level in the system reservoir.

## How synthetics stack up

Man-made lubricants are filling a need in industry, especially in areas where the hydrocarbon petroleum oils and greases just won't do. Here is a rundown on the more common types, what they are, what they cost:

**Silicones**
Well suited for high temperatures, boast a very high VI by conventional standards (see p 7). Cost: between $20 and $40 per gal.

**Polyglycols**
Used as engine oils, hydraulic fluids, high-temperature lubricants. Good lubricity characteristics. Cost: in the $2-6 per gal range.

**Silicate esters**
Feature high VI yet weak oxidation resistance above 400 F. They're sometimes used as high-temperature hydraulic fluids. Today's costs: $10-12 per gal.

**Phosphate esters**
High rating on oxidation resistance (up to 300 F), lubricity and fire-resistance. They're being used as F-R turbine fluids. Cost? Figure on $3-4 a gal.

**Dibasic-acid esters**
See service as instrument oils, grease bases, special hydraulic fluids, jet lubricants. They cost $3-10 a gal.

**Fluoro compounds**
Extremely high oxidation resistance and fire resistance, poor VI, good lubricity. If you're buying these compounds, expect to pay about $200 a gal.

## Fire-resistant turbine lubricants

Finding a suitable F-R lubricant for steam-turbine-generators has received high-level attention in recent years — for several sound reasons. Steam temperatures in central stations and some industrials exceed the autoignition point of mineral oil, 700-800 F. Also, the trend is toward ever-larger units. Success throughout industry with F-R hydraulic fluids has whetted the appetites of utility operators.

Although a check of fire records shows central stations have racked up a fine fire-safety score, utility operators are keenly aware of the potential threat if a lubrication line should break, a pressure gage or thermometer work loose near a steam line.

Since the initial wave of interest some ten years back, there have been many tests of F-R fluids in turbine-driven boiler-feed pumps and on bearings in manufacturers' shops. Full-scale operation in gas-pipeline pumping stations has been successful. In each case, the fluid has been a phosphate ester.

**Two questions** have plagued equipment builders and steam-plant operators: (1) Will the generator insulation hold up if fluid gets by the bearing seals? (2) Will the fluids do an adequate job of lubricating bearings under full load?

Present thinking indicates generator insulation is not really a problem with the newer insulation systems. Belief is that the phosphate-ester fluids will prove no more harmful on new insulations than petroleum oil did on the older asphaltic type — probably less so.

Bearing tests are another thing. Although the synthetics came through early tests with flying colors — even today's tests on thrust bearings are proving out — most recent studies pose unsolved problems in the journal bearing at full load.

# HYDRAULIC FLUIDS

If you could specify the ideal hydraulic fluid, its characteristics would read something like this: A good lubricant, fully compatible with all presently available bearing materials and sealants . . . high VI between −70 and 500 F . . . harmless to commonly used paints, metals, plastics . . . viscosity suitable for present hydraulic fits and clearances . . . stable with time and use while offering high resistance to mechanical shear . . . long life, fire-resistance, low price tag, high availability. This listing is somewhat academic since no fluid matches all these requirements. In real life you choose from listing at right, unless you can do with a synthetic non-fire-resistant hydraulic fluid.

**Petroleum oil** is the hydraulic fluid in widest use today. Next to water (which still handles some industrial jobs) oil is lowest cost, in plentiful supply, compatible with most materials found in hydraulic circuits. Additives can further extend the inherent VI, pour point, oiliness.

No single mineral oil fits all conditions economically. Operating temperature, leakage rate, amount and type of contaminants, fluid costs all come into the picture. A high-VI oil is desirable for many hydraulic applications since it can be used over a wider temperature range and yet meet limits established by the pump manufacturer. Bear in mind that low-VI oils also make excellent hydraulic fluids; they can be used in systems where temperature ranges are narrow (below a ceiling of 150 F). Color, flash point and carbon residue have little or no direct bearing on performance but are useful yardsticks for refiner, oil supplier and user.

**Water-oil emulsions** have won a name in recent years as fire-resistant hydraulic fluids. They are made by combining petroleum oil and water in varying proportions; suitable additives hold them in emulsion. Because of their high water content, steam forms when these fluid emulsions hit a high-heat source. Steam then acts as a blanket or snuffer to prevent the mineral oil from burning.

Unlike most synthetics, oil-water-emulsion fluids are normally compatible with all conventional packings and seals (exception: butyl-rubber packings). Leather may absorb water from the emulsion, tend to swell somewhat.

**Fluid selection** starts when you spell out the service conditions. Exposed outdoor hydraulic systems will demand fluid properties far different from an inside system facing constantly mild conditions. Leaky, poorly maintained systems (and there are many operating) can live with a less costly fluid since losses are constantly being replenished. In a tight, well-maintained system, the same fluid must be used over a long period and little is added; this calls for a higher-quality fluid. Get detailed requirements on lubricity, stability and other properties the pump builder recommends, then check with the fluid supplier.

# GREASES

New developments are characteristic of the grease industry: new greases formulated with new materials to handle new conditions. Along with the growing number of new greases, many old standbys are still going strong. Greases may be of petroleum origin or synthetic. In sharp contrast to the development of special products for special jobs is increasing progress in multipurpose greases.

**Greases are classified** by consistency, akin to using viscosity for a fluid lubricant. A soft grease, say No. 1 in the NLGI (National Lubricating Grease Institute) series, might run about 90% oil, water ranging from just a trace to 2%, and the remainder thickener and additives. On the other end, a stiff grease such as No. 5 NLGI may run 30% soap and 3% water, the rest oil and additives.

**Multipurpose grease** combines properties of two or more specialized greases to function over a broader range of conditions and applications. Most popular ones have a soap base of barium, lithium or calcium complex.

*Barium type* is low in cost, offers good water resistance, can operate continuously up to 275 F. It's well suited for most bearings, but high soap content restricts its use. Barium grease is not widely available today.

*Lithium base* handles temperature extremes, has excellent water resistance, is easily pumped. Some formulations boast extremely high mechanical stability.

*Calcium-complex* grease has a melting point over 400 F. It offers excellent water resistance, also resists breakdown and softening by working. Don't confuse this lubricant with the calcium-soap grease discussed below.

**Specialized greases** lack the wide application scope of multipurpose types. The many specialized greases include those made with soap base of calcium, sodium or a mixture of the two, aluminum or lead.

*Calcium-soap* grease offers good water resistance in general plant use up to 160 F. Above this temperature, grease loses the water it needs for stability and separates into the original oil and hard soap. High-melting-point types that hold up to about 225 F are also available.

*Sodium* grease is a widely used bearing lubricant, good for moderately high temperatures — up to 250-F continuous. It boasts excellent adhesive and cohesive properties.

*Mixed-base types* combine characteristics of calcium and sodium soaps. Temperature limits and general operating properties vary widely with the mixture of ingredients. Stable, oxidation-inhibited greases used in lubricated-for-life bearings are often of the mixed-base type.

*Aluminum-soap-base* grease is fairly water resistant, has tacky or adhesive qualities, can be used up to 180 F.

*Lead soap* combines EP characteristics with good water resistance. It's suited for heavy industrial machinery at temperatures to 175 F or higher.

**Synthetics** are also moving into the field. Many combine a synthetic fluid with a standard soap; others, such as silicones, are all-synthetic. One silicone grease, for example, is recommended for ball bearings at temperatures anywhere from −100 to 300 F; a second type covers −20 to 450 F. They are highly resistant to water, oxidation.

# How fire-resistant industrial hydraulic fluids compare with petroleum oil

### Fire-resistance poses need for standards

Few really standard tests are available today to effectively evaluate F-R fluids. While ASTM studies this matter, interim tests are used.

*Autoignition point* is carried out in accord with an already established ASTM procedure for petroleum oil.

*Spray flammability* calls for heating fluid to 140 F, spraying at 1000 psi through an oil-burner nozzle onto a hot (1200-F) steel plate. You can use an oxyacetylene torch, noting flammability within a 3-ft zone.

Other tests include molten-metal ignition, hot-exhaust manifold, burning wood block, electric discharge and compression ignition.

| | Petroleum oil | Phosphate ester | Phosphate ester base | Chlorinated hydrocarbon | Water glycol base | Water in oil emulsion |
|---|---|---|---|---|---|---|
| **Specific gravity, 60/60, F (ASTM D-1298-55)** | .85-.90 | 1.15 | 1.25 | 1.45 | 1.10 | 0.90 |
| **Viscosity, ssu, at 100 F (ASTM D-445-53T and D-446-53)** | 186* | 200* | 235* | 145 | 200* | 350-450 |
| **Viscosity, ssu, at 210 F** | 45 | 45 | 45 | 35 | — | — |
| **Pour point, F (ASTM D 97-57)** | 0 | 0 | +15 | +30 | −30 | — |
| **Water content, % by weight (ASTM D-1533-58T)** | — | — | — | — | 35-45 | 40 |
| **Shell 4-ball wear test (1-hr test at 75 C and 600 rpm) Scar dia at 40-kg load, mm, avg** | 0.70 | 0.52 | 0.66 | 0.50 | 1.03 | 0.76 |
| **Autogenous ignition point, F (ASTM D-286-58T, modified)** | 700+ | 1180 | 1190 | 1200 | — | — |
| **Hot manifold test, F (SAE AMS 3150B)** | 800 | 1370 | 1300+ | 1300+ | 1300+ | 1300+ |
| **Spray-flammability test (USBM Schedule 30)** | Fail | Pass | Pass | Pass | Pass | Pass |
| **Approximate cost, $ per gal** | $0.60 | $3.50 | $3.50 | $3.15 | $2.30 | $1.00 |

*These fluids available in a range of viscosities

# Three main components of grease and their working roles

### Oil is basic lubricant

Oil is generally most important of the three components since the grease takes on its inherent properties. Mineral-oil portion of a grease can vary widely in viscosity, type of stock, degree of refinement. Synthetic fluids are being used to cope with operating extremes.

Oils in grease range from light spindle type to heavy residuals. A few rules - of - thumb: Medium- to high-viscosity oils are generally used in greases slated for high-temperature or slow-speed service, light-bodied oils for more modest temperatures and high speeds. Many believe viscosity of oil in a grease should be the same as if an oil lubricant (rather than grease) were being used. But if pumpability is critical, a lower-viscosity oil may be in order.

The old theory compared thickener to a storehouse for oil — a sponge that gradually gives up its oil content. But that theory is being sidetracked. Recent thinking looks on grease as an intimate mixture of thickener and oil, both acting as lubricants.

### Thickener supplies body

Most common thickener used in grease today is soap formed or saponified by combining a fatty material with an alkali. The fat may come from an animal, marine or vegetable source: tallow, fish oil, cottonseed oil are typical. Alkaline portion of soap thickener may be oxides or hydroxides of the metallic elements: calcium, sodium, lithium, lead, zinc, for example. Ability of soaps to crystallize in fibrous form is the key to oil thickening as grease is made.

Soda, calcium and lithium soaps account for the largest volume of thickeners in industry today. Calcium and lithium are used in multipurpose, all three in special greases.

Non-soap gelling agents are on the increase. Inorganic compounds such as surface-treated clay or silica and organic compounds such as arylurea effectively thicken oils, producing high-melting-point greases. The non-soap thickeners are usually mixed with oil and the mix passed through a colloid mill to produce an intimately dispersed homogeneous grease.

### Additives enhance properties

Grease made simply from oil and thickener is often suitable for more modest industrial lubrication requirements. However, additives improve certain characteristics of the grease. Typical ones are tackiness, oxidation stability, consistency stability, load-carrying capacity, rust prevention. Materials called *fillers* are also added to grease to further extend its properties: graphite, molybdenum disulfide, asbestos, talc, carbon black, zinc oxide, clay are typical. In this report we consider all materials mixed with oil and thickener as additives, since they are placed there to improve the basic grease, let it work over an extended range or extreme conditions.

Many grease developments racked up in recent years are due in part to modern additives. Oxidation resistance has improved at high temperatures, life expectancy of the grease extended 8- to 10-fold. New greases suit the range between −100 and 450 F. Truly effective rust inhibitors have been produced for calcium- and lithium-base greases.

# Today, many materials are working as solid lubricants

## Inorganic compounds include graphite, molybdenum disulfide, phosphate coatings

**Laminar materials** like graphite and molysulfide depend for lubricating action on the weak bond between layers. Other examples: tungsten disulfide, mica, boron nitride, borax, silver sulfate, cadmium iodide, lead iodide. Planes of a graphite lubricant must be separated by an adsorbed film (usually water, sometimes oxygen or $CO_2$). Otherwise high friction results, unless an additive is used.

No materials in this class give permanent protection against wear when applied as a rubbed-on film, but molysulfide lasts longest. Both graphite and molysulfide are chemically inert when free from contaminants, but neither gives corrosion protection as a rubbed-on film.

*Soft solids,* really not classified as laminar, include lead carbonate as a threading compound, talc and bentonite as solids in greases. Lead monoxide appears the most promising solid lubricant between 430 and 650 C.

**Chemical conversion coatings** on metal surfaces supplement other lubricants. Some form at points of incipient seizure, a reaction between EP additives and loaded surfaces.

Phosphate coats (mainly zinc with small amounts of iron and manganese) can be applied to alloys of iron, aluminum and zinc. They're used in metal forming and working. Others are sulfide, chloride, oxide, oxalate. But films in this class are thin, often brittle, hard—not ideal solid lubricants.

## Organic materials such as polymer films are also on the job

**Polymer films,** relative newcomers as solid lubricants, show wide promise. Polytetrafluoroethylene and polychlorofluoroethylene both give low friction, prevent wear under moderate loads and speeds when used as thin films on metal.

**Thin film of soft metal** on a hard base has some lubricity. Example: about 4 x $10^{-4}$ cm indium on tool steel. Adequate metal film must be thicker than an oily organic, but in either case wear life increases with thickness, decreases with load.

**Soaps, fats, waxes** include metallic soaps: aluminum, zinc, calcium, magnesium, sodium, lithium stearates; fatty acids: stearic, palmitic; beeswax, spermaceti wax, synthetics. Most waxes and fats can be applied through a lubricating solvent. Some materials in this class are self-healing, though at a much lower rate of repair than liquid lubricants and greases. Microcrystalline waxes, for example, are effective light-duty lubricants below their melting points. Others, more chemically active, give good results on base metals even above their melting points—react with the surface to form a compound.

# SOLID LUBRICANTS seek new uses as dry

A solid lubricant is simply a solid material placed between two moving surfaces to prevent metal-to-metal contact, thus reduce friction and wear. Applications for solid lubricants lie in the boundary and mixed-film area. In the hydrodynamic region there is no wear—only fluid friction. Yet in everyday practice it's tough to avoid some piercing of the oil film, at least on startup and shutdown . . . further extending the role of solid lubricants.

**Properties** of the solids will naturally vary considerably from fluids we discussed on pp 6-7. To reduce friction and wear the ideal solid lubricant would have low shear strength, high elastic-strain limit, excellent adhesion to base material, good film continuity to prevent metal-to-metal contact plus self-healing qualities to allow film to reform immediately if broken. There would be no abrasive impurities. It is highly improbable that all these will be found in any one solid lubricant.

**Life factors** for solid films hold only if the film remains continuous. Moving layers of solid film are going through the same internal process of weld-breaking, pick-up and transfer that occurs between poorly lubricated bearing surfaces, so life of the solid film is not indefinite. When the end comes it is characterized by a rapid increase in friction and serious galling of the metal beneath. That's why it's important to design equipment employing solid films so film life span falls well within the life of the lubricating solid. Unfortunately there is no standard test method to evaluate life of a solid lubricating film. But there are other properties that must be considered:

*Thermal stability* is significant since solids are often considered for jobs way beyond the limits of petroleum lubricants. *Chemical inertness* enters the picture—the solid lubricant should not react with substrate or atmosphere.

If *melting point* is exceeded, strong lateral attraction between molecular chains of the solid film is destroyed, leaving little to prevent metal-to-metal contact. This means the organic solids will lose much friction-fighting ability.

*Heat conductivity* comes to the fore when considering plastics for solid film or bearings. Plastics don't conduct heat well, so high surface temperatures cause local melting and some gathering up of the material. One possible answer, at least for plastic bearings, is mixing metal powder with the plastic to improve heat transfer.

*Electric conductivity* must be considered. Where lubricants are used on sliding contacts, conductivity must be high; low when insulators face rubbing contact.

**Graphite dispersions** see service across industry. Colloidal graphite is available in water, wax emulsions, petroleum oil, castor oil, mineral spirits, other solvents.

The graphite-water combination is used for lubricating dies, tools, metalworking molds, oxygen equipment and for wire-drawing. Graphite-oil dispersion handles general industrial applications. Graphite-and-solvent is used as a parting compound for gaskets; for drawing, extruding

# in an expanding field, applied in different forms

## Five ways to use solid lubricants

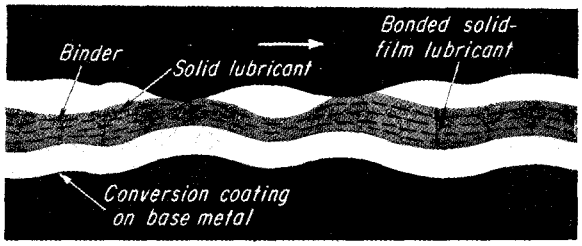
**As additives**
Graphite, molybdenum disulfide and zinc oxide are widely used, added to fluids and greases. Surface-conversion coatings often supplement other lubricants.

**For incompatible environments**
This area is getting increasing attention, especially for threads, valves, seals in rocket-propulsion mechanisms exposed to liquid oxygen. Examples in industry: bearings exposed to chromium plating; steam; solvents; chemicals in pumps, meters, mixers.

**At extreme temperature and pressure**
March into space highlights this area: temperatures of sliding surfaces may range from −350 to 3500 F in devices now planned, pressures vary from atmospheric to full vacuum. Back on earth, bearings on conveyors passing through kilns are candidates for the solids, as are bearings—regardless of temperature or pressure—near surfaces which cannot be contaminated.

**Under intermittent loading**
Where equipment may be stored or sitting idle, lubrication must be permanent, non-dust-collecting, noncorrosive. Fretting corrosion—an ailment met in rolling bearings exposed to vibration—may be sidestepped. Sliding electric contacts are a prime target for solid lubricants.

**Where bearings are inaccessible**
Where a bearing can't be serviced because of its location, solids may work if loads, speeds are reasonable.




## What is a bonded solid lubricant?

As a class, solid lubricants alone lack power to adhere to the surfaces they're protecting—probably the main reason for low wear life of rubbed films. But low adhesion can be overcome by mixing the solid lubricant with a bonding agent. Mixture is generally dispersed or dissolved in a solvent, sprayed on, then baked.

Many organic binders have been tried: corn syrup, acryloid, vinyl, acrylic, silicone, alkyd, phenolic and epoxy resins. The last two appear most popular to date, with silicones favored for some h-t jobs. About 600 F is maximum operating temperature for bonded coatings, but inorganic binders promise to extend this figure.

A molysulfide-graphite mixture, bonded with sodium silicate onto the race and retainers of otherwise-unlubricated 204 ball bearings, has increased life from minutes to 240 hr at 1250 rpm, 29 hr at 10,000 rpm, 350 F.

# films, chemical and bonded coatings, additives

and stretch-forming aluminum and magnesium; as a h-t lubricant for conveyor chains and bearings.

**Molybdenum disulfide** has grown in the past decade from a relative newcomer to a ranking member of the broad family of industrial lubricants. Its lubricating action comes from a unique molecular structure. Each *lamina* of the material is composed of a layer of molybdenum atoms flanked on either side with a skirt of sulfur atoms. Sulfur bonds strongly to metal, so one of the sulfur layers hangs onto the metal surface. But the sulfur-to-sulfur bond is weak, so other side slides easily over adjacent molecules.

$MoS_2$ dispersions can be had in water, polyalkylene glycol, isopropanol. Petroleum-oil dispersion is recommended for general use involving EP, high temperature.

**The many application methods** can be boiled down to five basic schemes: (1) Deposition from a liquid phase by thermochemical action with the metal surface. EP and hypoid gear oils deposit compounds of chlorine, sulfur and phosphorus in this manner. (2) Solids are dispersed in liquids, then carried to the boundary areas—colloidal $MoS_2$ and graphite dispersions, zinc-oxide greases are typical. (3) Chemical pretreatment develops inorganic crystalline layers—oxides, sulfides, phosphates, chromates. (4) Dry solids are applied directly by rubbing, burnishing, tumbling. (5) Coatings bond larger quantities of solids.

However applied, solid-lubricant particles coat the boundaries of actual contact to reduce friction. The laminar materials such as graphite and $MoS_2$, with their layered structure, shear easily in the direction of flake flatness yet resist pressure and penetration in the other direction.

**Temperature** is critical in applying solid as well as other forms of lubricants. For example, resin-bonded coatings deteriorate rapidly as temperatures climb beyond about 200 F. This is probably due to softening and oxidation. Coatings have been developed which promise satisfactory life to 600 F, but above this level, binders need further improvement.

$SiO_2$ and $B_2O_3$ bonded coatings show relatively high friction and wear resistance from room temperature to the point where molten glass forms in the wear track—around 500 F for high-speed operation. As temperature increases above the softening point of the glass, wear life decreases, first slowly, then rapidly. Although it's superior to resin-bonded lubricants, life of sodium-silicate-bonded lubricants also decreases with increasing temperature.

**In low-temperature operation,** solid lubricants as a class are effective down to where organic lubricants become too viscous or solidify. PTFE (Teflon) and compounded-PTFE films are satisfactory in liquid nitrogen, as are sodium-silicate-bonded molysulfide-graphite coatings in liquid oxygen. PTFE films tend to spall off at liquid-nitrogen temperatures, but that can be prevented by compounding to decrease the differences between coefficients of expansion of the coating and substrate material.

## The never-ending search for even better lubricants

Man's search for effective lubricants is as old as recorded history, and so far it shows no signs of slowing down. Countless materials have been tried in field tests, discarded after their shortcomings became known, replaced by better ones. Yet many of today's lubricants are surprisingly old when traced to their origin.

The Egyptians boiled up a mixture of animal fat and calcium soap to grease chariot wheels in 1400 BC. Even before that, in 3500 BC, the Chinese used water as a lubricant (we recently reported on how hard carbide bearings and journals take water-lubrication problems in stride). Then the Chinese went on to mix vegetable oil and calcined lead, which proved out very nicely in 770 AD. Even the idea of air as a lubricant was suggested over a century ago.

The point we are making—sort of a designer's truism—is that current needs help create the product. Problems now being evaluated in the broad area of space lubrication were barely considered some years back: The need for space lubricants just didn't exist.

Gaseous lubrication, with air as the lubricant, is in practical use today for conditions most lubricants can't meet: high-speed light-load applications like ultracentrifuges, high-speed grinding spindles, gas circulators for nuclear reactors. Researchers are hard at work on problems associated with gaseous lubrication of gyroscopes, dynamometers, high-speed textile spindles, electric motors, gas turbines, jet engines and missiles.

Air, helium and $CO_2$ are about the only gases in active use, but many other gases and vapors are being investigated. In this grouping are halogenated hydrocarbons, sulfur hexafluoride, nitrogen, organic vapors. Vapor lubrication using steam for steam turbines is being studied.

Radiation-resistant lubricants have come into the spotlight. As emphasis is placed on using the atom, the search widens for materials that can survive in a radiation environment. Today there exists a relatively small but quite definite need for radiation-resistant lubricants in nuclear-power plants. In many cases reactor designers have been forced to avoid use of organic lubricants. New lubricants had to be developed; now they're proving out in service. And thus the quest continues for better lubricants to meet new and challenging jobs of fighting friction.

## How tough are the problems of lubrication in space?

**Initial hurdle is really understanding the outer-space environment in which moving surfaces and lubricants must work.**

**Air temperature after launch drops to about —55 F, rises to 260 F at 40 miles. Once vehicle is free of atmosphere, side exposed to the sun is heated while shadowed side is not. On the moon, temperature changes through a 450-F range pose problems of heat transfer, fluid flow in lubricant.**

**Next, assume the lubricating system will operate in hard vacuum. This means eliminating shaft seals between working fluids and environment. Materials with high rates of evaporation must be avoided; vacuum may cause volatile components, adsorbed gases, conventional oils and greases to evaporate off.**

**In deep space you must face up to radiation: solar rays, cosmic rays and radiation from on-board nuclear-power sources. Metals and their alloys are fairly resistant but the organics are notably susceptible. Within the craft, weightlessness is a factor: oils tend to creep, hydraulic systems must be closed.**

**Not all space conditions can be duplicated in a lab — ultimate test will be aboard the spacecraft. But lubrication engineers must try to think of all angles in advance, to insure top reliability once craft is in space or on other planets. Lubricant suppliers have spent years of hard work on the many space problems. National Aeronautics and Space Administration, the armed services and some 50 industrial and research organizations are currently tackling lubrication-in-space.**

**The answers, although not complete by a long shot, are starting to take shape. In the solid-film area, a combination of $MoS_2$-graphite-sodium-silicate is being weighed. Its characteristics: temperature range between —300 and 1200 F; undamaged by gamma radiation of 5 X $10^9$ roentgens; lubricates under high vacuum. Precious metals and ceramics are being looked at as load-bearing surfaces. Gas as a lubrication fluid is getting serious consideration. And some propose eliminating lubricants altogether, replacing them with electromagnetic suspension.**

**For heavier loads, however (and turbine-generators using nuclear energy seem most likely source of electric power), the emphasis is swinging to liquid-metal lubricants. Likely prospects: mercury and NaK. But no ideal solution is at hand. In space, as on earth, no single lubricant can do it all.**

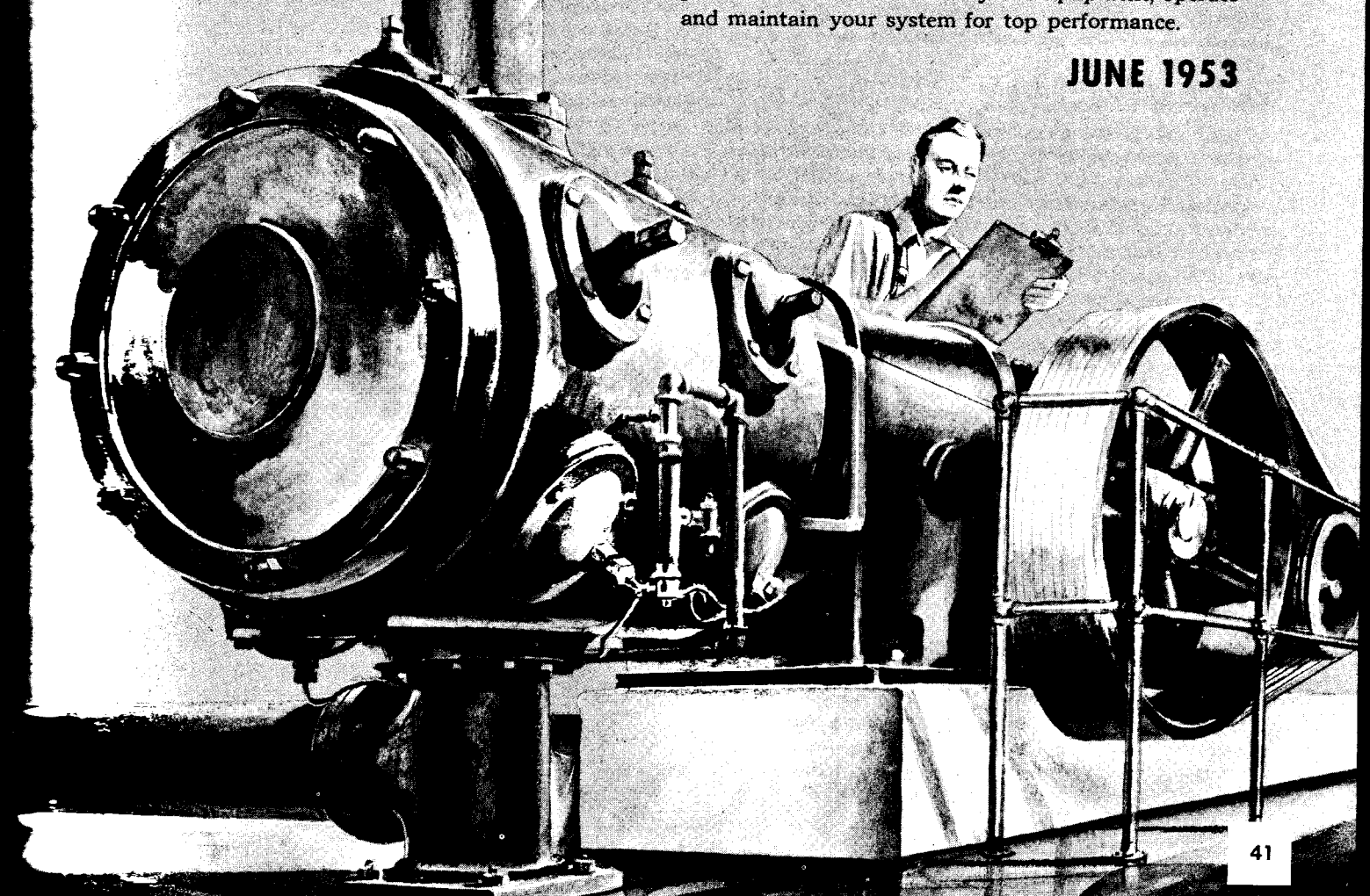
a **Power** handbook

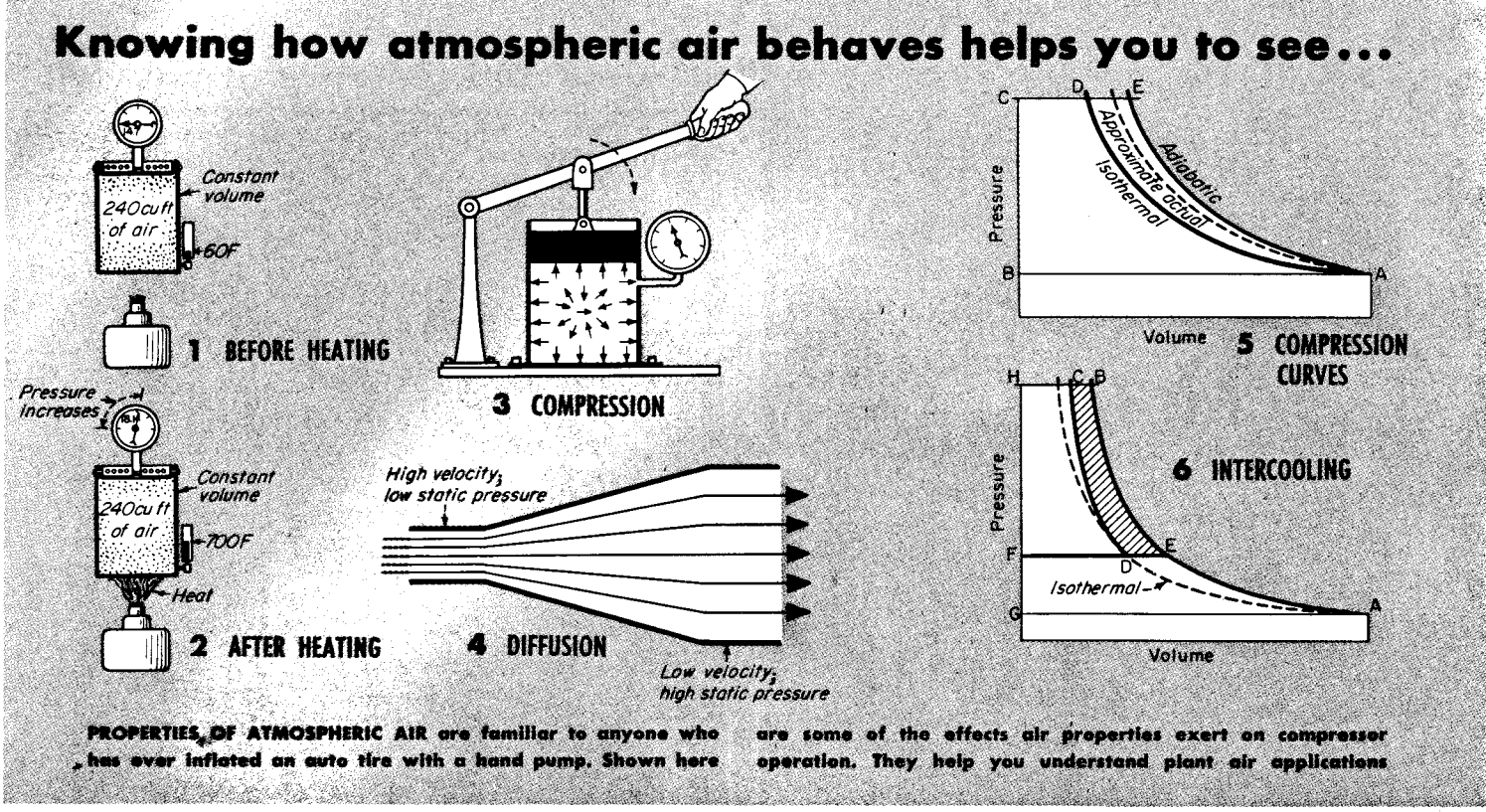
# Compressing Air

Compressed air powers a growing array of tools and devices, operates delicate instruments, agitates and atomizes liquids, blows soot, conveys materials. And it takes on new jobs every day.

It's hard to find a plant where this versatile power service isn't put to good use, an engineer who doesn't have responsibility for an air system — large or small. So here, for all POWER readers, is a handbook covering the compressors that take in atmospheric air and give it the pressure boost that makes it useful, the auxiliaries needed for good compressor operation, the distribution system that puts air to work throughout the industrial plant. Use it to select and lay out equipment, operate and maintain your system for top performance.

**JUNE 1953**






**PROPERTIES OF ATMOSPHERIC AIR are familiar to anyone who has ever inflated an auto tire with a hand pump. Shown here are some of the effects air properties exert on compressor operation. They help you understand plant air applications**

# How Compressors Work

Air compressors have but one diet — atmospheric air. So performance depends on its properties. Let's take a quick look at some of them important to compressor operation.

## Atmospheric Air

Air is a mechanical mixture of gases, mainly oxygen and nitrogen. And atmospheric air always contains some water vapor. To see how air behaves, remember it consists of individual molecules of oxygen and nitrogen, widely separated compared with their size. Always traveling at high speed, at normal temperatures, they strike against enclosing surfaces and produce what we know as pressure, Fig. 1.

**Temperature** affects average molecule speed. When we add heat to a fixed volume of air, Fig. 2, molecules travel faster. So they hit containing walls harder and oftener. This shows up as greater pressure.

Now if we take a fixed mass of air and squeeze it into less space, molecule travel is restricted. There's no speed change, but molecules hit walls with greater frequency. So pressure is greater.

If, instead of a slow squeeze, we compress air rapidly, temperature rises as well as pressure. The fast-moving piston delivers energy to the molecules just as a bat delivers energy to a baseball. Higher molecule speed results, and this always means higher temperature.

Compression efficiency is compared against two theoretical standards — *isothermal* and *adiabatic*. Neither occurs in an actual compressor because of unavoidable losses. Plot of compression process on a pressure-volume diagram, Fig. 5, shows an actual unit works between these two standards.

*Isothermal compression* has perfect cooling — air remains at inlet temperature while being compressed. Work input to compressor, measured by area *ABCD*, is least possible.

**Adiabatic compression** has no cooling; temperature rises steadily during compression. Discharge pressure is reached sooner than with isothermal compression. Since air pressure is higher during every part of piston's stroke, more work input is needed, as shown by area *ABCE*, Fig. 5.

**Intercooling.** If compression is divided into two (or more) steps or *stages*, air can be cooled between them. This *intercooling* brings actual compression line closer to isothermal line, Fig. 6. Area *BCDE* shows power saved.

Atmospheric air, as we saw, contains water vapor in varying quantities, depending on location, weather, etc. Since a compressor cannot separate moisture from its intake air, let's see how water vapor affects the air delivered.

**Water vapor** in atmospheric air exerts a pressure separate from that of the air alone. Total atmospheric pressure is the sum of the air pressure and the vapor pressure.

Suppose we have 80-F air saturated with water vapor. In this state, the air contains all the moisture it can hold at this temperature. Any added vapor would condense.

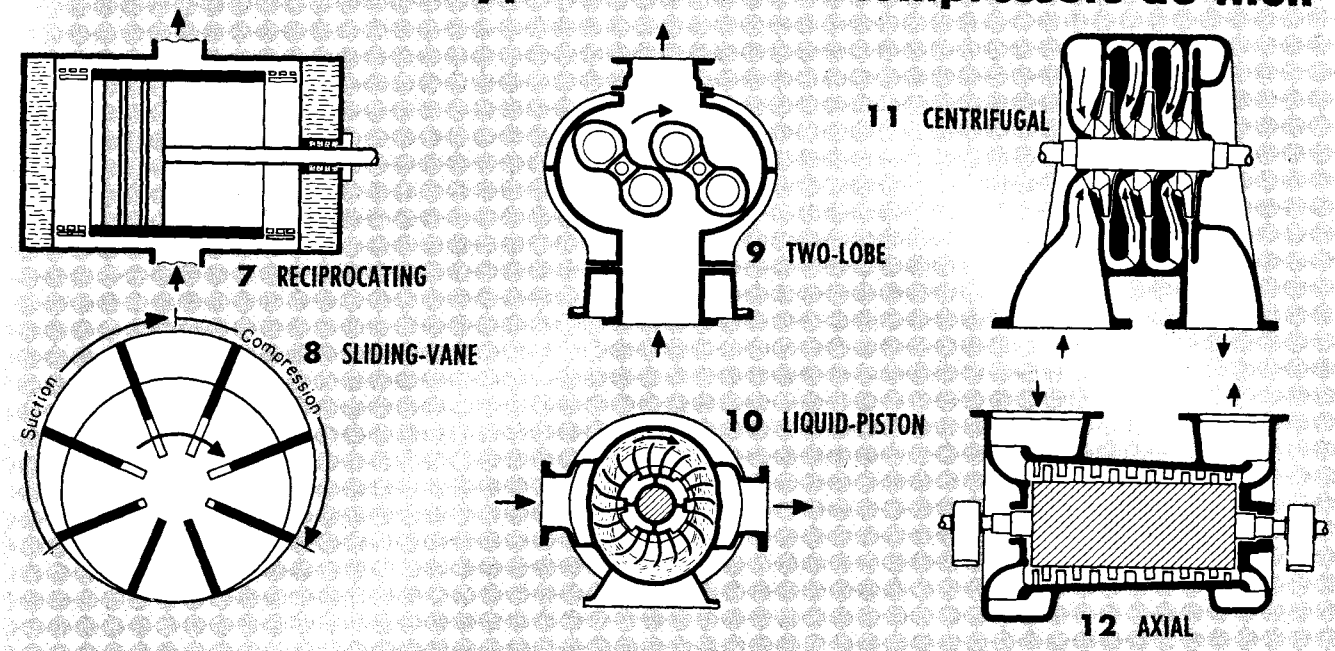
If total atmospheric pressure is 14.7 psia, pressure exerted by air alone must be the difference between 14.7 and vapor pressure at 80 F. Latter is same as saturated steam pressure at 80 F and shows in the steam tables as 0.507 psia. So air pressure is 14.7 — 0.507 = 14.19 psia.

**Partially saturated air** contains less than the maximum amount of water vapor that can be held. Amount of moisture is measured by *relative humidity*. If our 80-F atmospheric air has a relative humidity of 70% it holds only 0.7 as much water as it could. Vapor pressure is 0.7x0.507, or 0.355 psia. Air pressure is 14.7 — 0.355 = 14.35 psia.

Water vapor in air entering compressor leaves as a superheated vapor because its temperature is in excess of that corresponding to its pressure. It can be converted to water only by cooling to a temperature below the saturation temperature corresponding to its pressure.

Immediate cooling of air after it leaves the compressor

# ...how these basic types of modern compressors do their job




**SIX COMPRESSOR TYPES diagrammed find many different uses in modern industry. Each has its advantages and gives best results on jobs where it suits the needs. Wise choice of compressor type is one of the keys to years of good performance**

proves best, because this prevents vapor from reaching distribution system. Either air- or water-cooled heat exchangers, called *aftercoolers* (p 96), are used for this.

## Modern Air Compressors

Each of the two major design classifications—*positive displacement* and *dynamic*—has its advantages.

In positive-displacement compressors, Fig. 7-10, successive volumes of air are confined within a closed space, and pressure is increased by reducing volume of space. Units of this type may be further classified as *reciprocating* or *rotary*, and these, in turn, subdivided by design features.

**Reciprocating compressors**, Fig. 7, suck air into cylinders through valves, during the *suction* stroke. At end of *discharge* stroke, air leaves at higher pressure. Separate valves are provided for inlet and outlet.

**Sliding-vane rotary** compressor, Fig. 8, traps air between vanes as rotor passes inlet opening. As rotor turns toward discharge port, volume of cell between any two vanes decreases. This causes air pressure to rise to rated discharge value. Vanes slide in and out of slots as rotor turns, are held against casing by centrifugal force.

**Two-lobe rotary** compressor, Fig. 9, has identical impellers held in a fixed relationship to each other by external gears. When impellers rotate, each traps air between its outer surface and the casing. When impeller upper tip passes top edge of casing it permits discharge to begin. Bottom tip of impeller pushes enclosed air into discharge piping, compressing it against the backpressure.

**Liquid-piston rotary**, Fig. 10, has a round multiblade rotor revolving in an elliptical casing partly filled with liquid, usually water. When rotor turns it carries liquid around with it, the blades forming a series of buckets. Because liquid follows casing contours, it alternately leaves and returns to the space between blades (twice each revolution). As liquid leaves bucket, air is drawn in. When liquid returns it compresses air to discharge pressure.

Dynamic compressors use rotating elements to accelerate air. By diffusing action, velocity is converted to static pressure. Fig. 4 shows basic idea. Total energy in a flowing air stream is constant. Entering an enlarged section, flow speed is reduced and some of velocity energy turns into pressure energy. Thus static pressure is higher in the enlarged section. Dynamic compressors include centrifugals, axials, and mixed-flow designs.

**Centrifugal compressors**, Fig. 11, usually take in air at impeller eye, accelerate it radially. Some static pressure rise occurs in impeller, but most is in diffuser section of casing, where velocity converts to static pressure.

**Axial-flow compressors**, Fig. 12, accelerate air in a direction generally parallel to the shaft. Units resemble turbines; each pair of moving and stationary blade-rows forms a stage. Pressure rise per stage is relatively small.

### DEFINITIONS

**FREE AIR** is air at atmospheric conditions at any specific location. Since altitude, barometer and temperature may vary, this term does not mean air under uniform or standard conditions.

**STANDARD AIR** is air at 68 F with a pressure of 14.7 psia and a relative humidity of 36%. Gas industries usually consider 60-F air as standard.

**DISPLACEMENT** of a compressor is volume displaced per unit of time, usually stated in cubic feet per minute (cfm). Multistage compressor displacement is that of the low-pressure cylinder only.

**CAPACITY** is actual delivery in cfm of free air.

**STATIC PRESSURE** of air is measured so air velocity has no effect on the reading.

**TOTAL PRESSURE** is that produced by stopping a moving air stream.

**VELOCITY PRESSURE** is total pressure in a moving air stream, minus the static pressure.

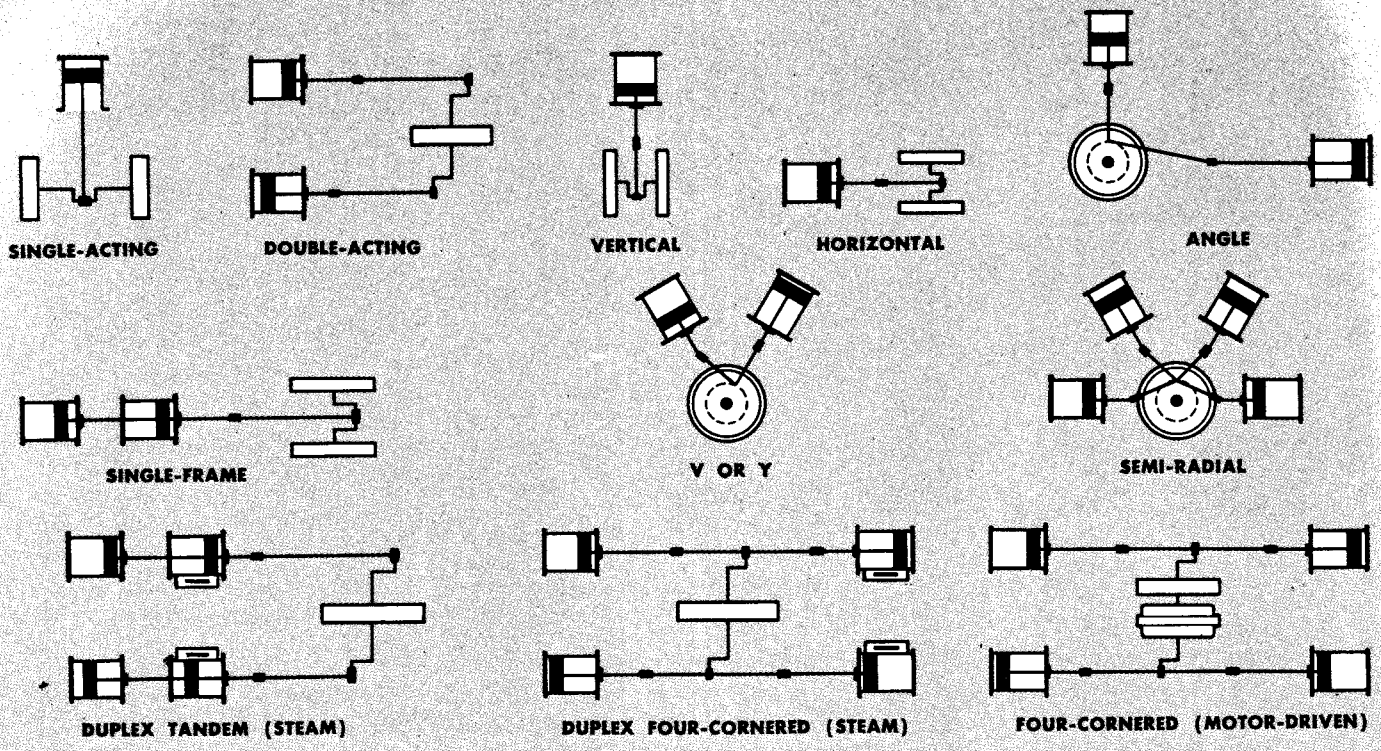
**INLET PRESSURE** is absolute total pressure of compressor inlet.

**DISCHARGE PRESSURE** is absolute total pressure at discharge.

**INTERCOOLING** is removal of heat from air between compressor stages or stage groups.

*(Adapted from Compressed Air and Gas Institute definitions)*

## Some typical frame and cylinder arrangements used today




# Reciprocating Types

Arrangement of reciprocating-compressor frames and cylinders varies with capacity, discharge pressure, intended service, drive, and other factors. Sketches above show many of the arrangements in use today.

## Arrangements

*Single-acting* compressors use only one end of the cylinder to raise air pressure; *double-acting* units use both ends of the cylinder and discharge twice as much air per cylinder per revolution of the crankshaft.

*Single-stage* compressors raise air pressure from inlet to discharge on each working stroke of the piston in each cylinder. *Two-stage* units use one cylinder to compress air to an intermediate pressure and another to raise it to final discharge pressure. When more than two stages are used, the compressor is called a *multistage* unit.

*Vertical* compressors and *horizontal* units are arranged as shown. *Angle* type are multicylinder with one or more horizontal and vertical compressing elements. *Single-frame* (straight-line) units are horizontal or vertical, double-acting, with one or more cylinders in line with a single frame having one crankthrow, connecting rod and crosshead.

*V* or *Y type* are 2-cylinder, vertical, double-acting machines with cylinders at some angle with vertical, usually 45 deg. Single crank is used. *Semi-radial* compressors are similar to V or Y type but have horizontal double-acting cylinders on each side.

*Duplex* compressors have cylinders on two parallel frames connected through a common crankshaft. In *duplex-tandem steam-driven* units, steam cylinders are in line with air cylinders. *Duplex four-cornered steam-driven* compressors have one or more compressing cylinders on each end of frame and one or more steam cylinders on opposite end. In *four-cornered motor-driven* units, motor is on a shaft between compressor frames.

## Elements

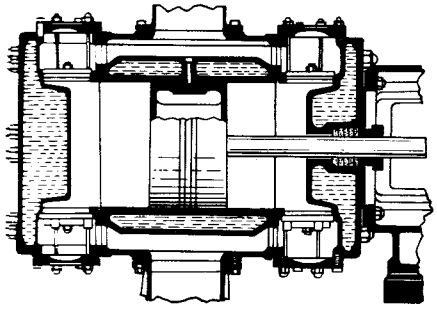
These are, briefly: (1) cylinders, heads, pistons, inlet and discharge valves (2) power-transmitting parts, including piston and connecting rods, crosshead, crankshaft, flywheel (3) lubrication system (4) cooling system (5) controls. First three groups are discussed on this and next three pages.

**Cylinders.** Drawings opposite show some typical designs. Valves may be in cylinder or in head. Water-cooled compressors have jacketed bores; air-cooled units have fins cast integral with cylinder. Cylinder material depends on discharge pressure: cast iron or steel up to 1000 psi, forged steel or alloys for higher pressures. Integral cylinder barrels permit at least one reboring without weakening walls.

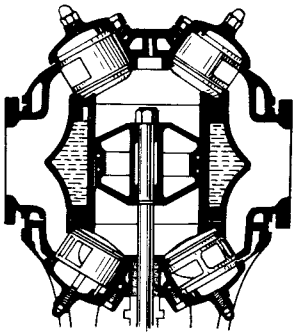
**Pistons** are usually semi-steel, close-grained cast iron, or aluminum. Trunk pistons, without crossheads, are used on single-acting compressors. Double-acting pistons are solid or hollow, with box or truncated shapes. Crosshead construction permits sealing compressing element nearer running gear. Packing to prevent air leakage along piston rod may be metallic, composition, carbon or fibrous, depending on service. "Oilless" compressors use carbon piston rings or liners, instead of metal, need no cylinder lubrication.

**Valves** of automatic type open and close on pressure difference. They consist of a plate, channel or strip with a seat and guard. Certain types are fitted with springs. Some designs of single-acting compressors have cam-operated poppet-type inlet valves.

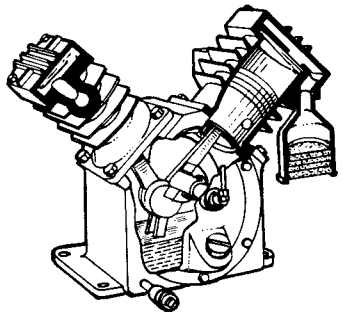
## CYLINDERS AND JACKETS



HORIZONTAL compressor cylinder: triple walls, valves in head, jacket handholes

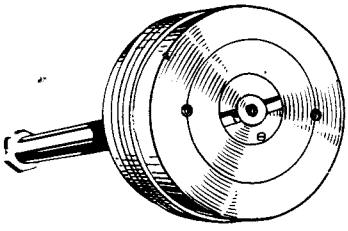


VERTICAL compressor cylinder with separate heads, water-cooled stuffing box

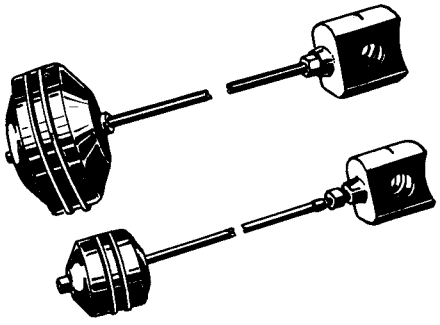


AIR-COOLED 2-stage compressor has fins on cylinders for greater radiating area

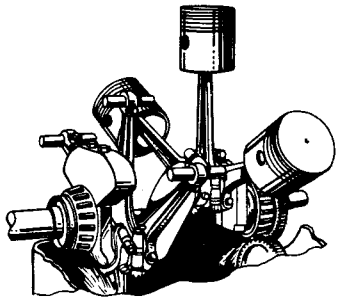
## PISTONS AND RODS



HOLLOW double-acting piston with lock on top, easily taken off rod for checks

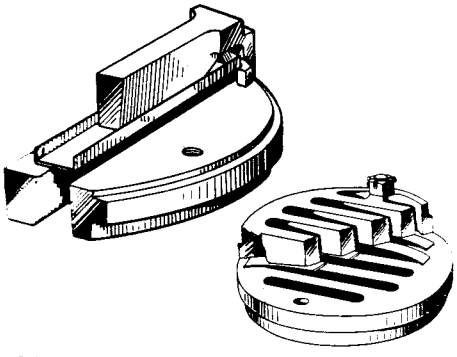


STEEL piston rods here are press fits, secured by jamb nuts on top of piston



TRUNK pistons for 2-stage air-cooled compressor. Three run on one crank throw

## SUCTION AND DISCHARGE VALVES



CHANNEL valve, *top*, has shaped elements; strip valve, *bottom*, flat ones

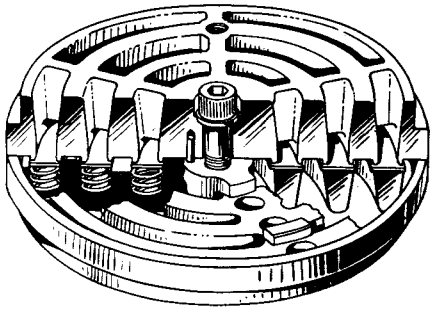
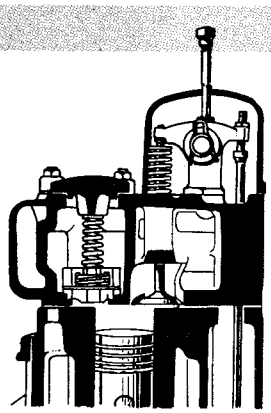
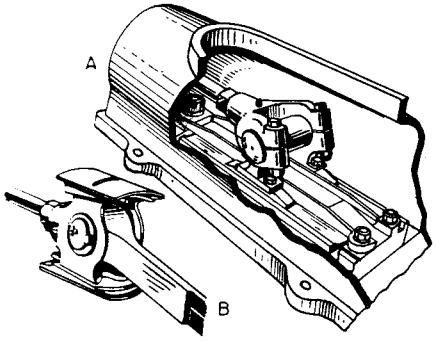


PLATE valve is fitted with cushioning springs to make sure plates seat gently

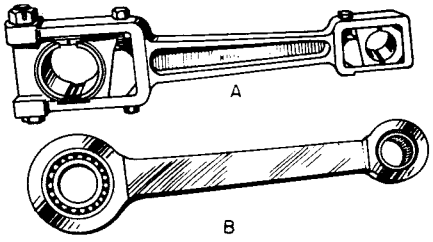


POPPET intake valve here is operated by a push rod and rocker arm from camshaft

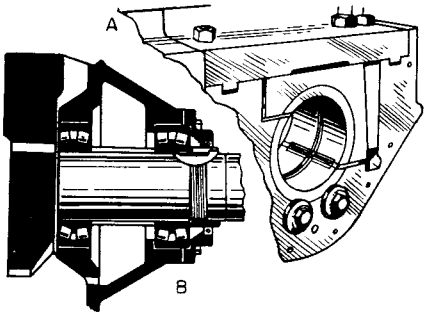
## CROSSHEADS, CONNECTING RODS AND BEARINGS




SINGLE SHOE, at *A*, takes downward rod thrust. Other designs have two shoes, *B*




FORK-END connecting rod, *A*, has wedge adjuster. *B* has roller, needle bearings




SPLIT-BLOCK type, *A*, is wedge adjusted. *B* has double heavy-duty roller bearings

# Stationary

Standard stationary compressors, intended for installation on more or less permanent foundations, are built in a number of types: (a) Vertical or V single-acting units, either air- or water-cooled, and single- or 2-stage, are available in sizes up to 150 hp. (b) Double-acting units, of vertical V, Y, semi-radial or right-angle types, and single-stage or multistage, come in 60-hp and larger sizes. They are water-cooled. (c) Double-acting units of single-frame type, horizontal or vertical, single-stage or multistage, range in size up to 125 hp, are water-cooled. (d) Duplex horizontal double-acting compressors, water-cooled and single-stage or multistage, run 75 hp and larger. Photos on these two pages show a few of typical designs available today.

**Single-Acting.** Fig. 1 and 2 show two examples of this design. Vertical unit, 1, mounts on its receiver, is air-cooled. Single-stage, its maximum pressure rating is 150 psi in the ¼- to 15-hp range. Two-stage air-cooled tank-mounted units are available for pressures to 200 psi.

Water-cooled unit, 2, has motor, compressor and radiator on a single base for direct mounting on plant floor. Pressure rating is 100 psi, capacity to 420 cfm at 100 psi.

**Double-Acting.** Right-angle crosshead-type 2-stage water-cooled unit, in Fig. 3, is rated at 80 to 125 psi with a displacement of 2397 cfm at 350 hp. Vertical V unit, Fig. 4, has a normal pressure rating to 125 psi and a displacement of 368 to 1828 cfm, depending on number of cylinders.

Single-frame units like that in Fig. 5 are built in a wide range of capacities for normal 100-psi plant service. Drive is usually an electric motor.

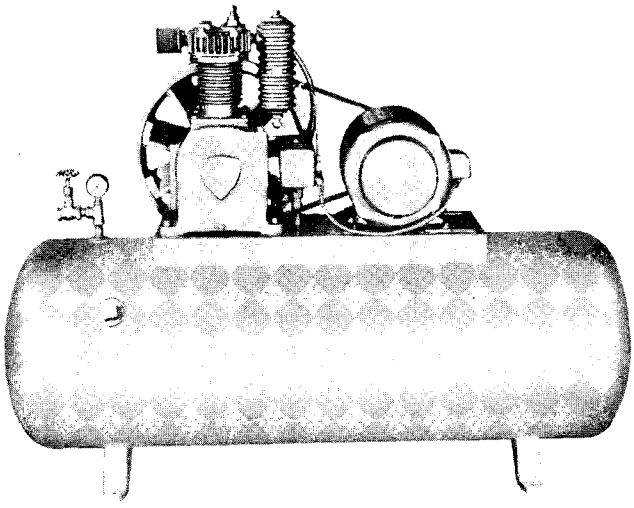
Duplex compressor, Fig. 6, offers capacities from 350 to 10,000 cfm, at pressures from 80 to 125 psi.

**Other Types.** In addition to types mentioned there are a number of other designs widely used for various jobs. Multistage, multicylinder, opposed units, Fig. 7, are built for pressures to 6000 psi, ratings to 5000 hp.

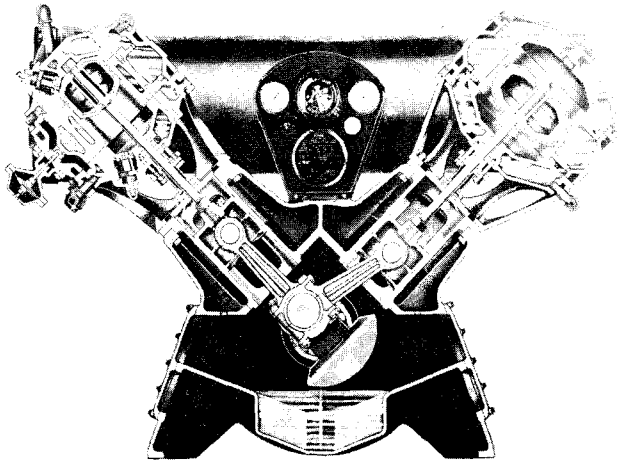
Oilless compressors, Fig. 8, are used where air free from oil is needed. Design shown has a carbon cylinder liner backed with steel. Piston rings are metallic. Compressor cylinder needs no lubricant. Other designs have a tail-rod and bearing to make piston free-floating; piston rings are made of carbon. Another construction has carbon pistons.

Engine-driven compressors, Fig. 9, have a vertical or V engine (gas or diesel) driving horizontal compressor pistons, in double-acting cylinders.

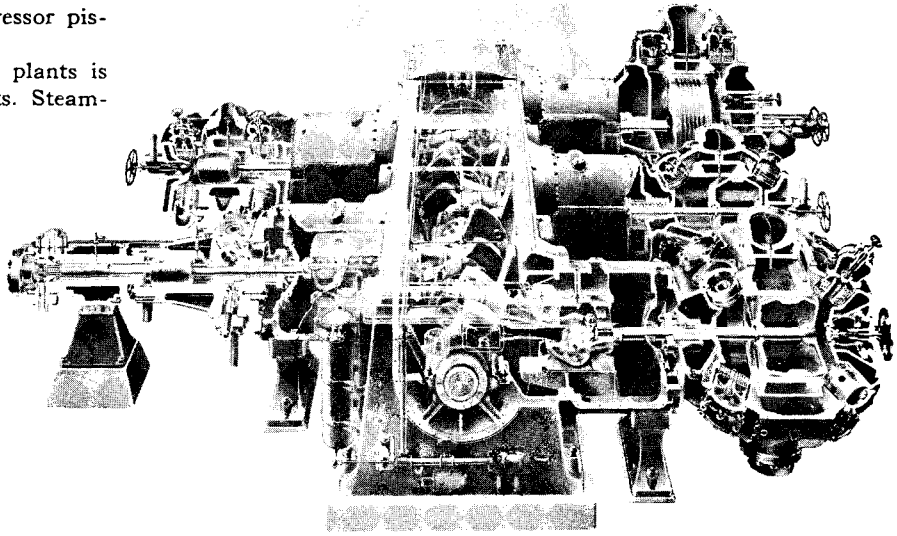
Another type of compressor popular in some plants is similar in design to locomotive air-brake units. Steam-driven, it mounts on wall, takes but little space.



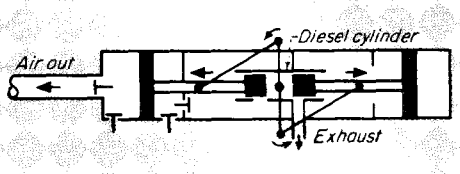
**1** Single-stage single-acting air-cooled compressor, with a 150-psi pressure rating, ¼- to 15-hp range, is on receiver



**4** Vertical V unit has two or four cylinders, depending on capacity desired. Pressures range to 125 psi, cfm to 1828

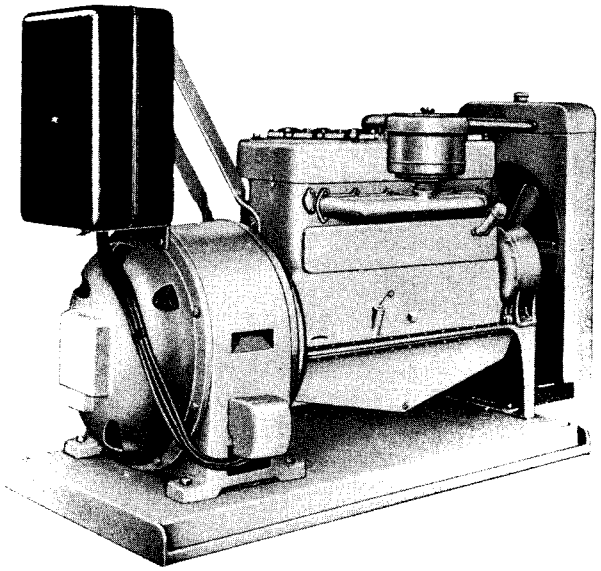


**7** Multistage, multicylinder, opposed unit is built for pressures to 6000 psi. Other types also handle high pressures

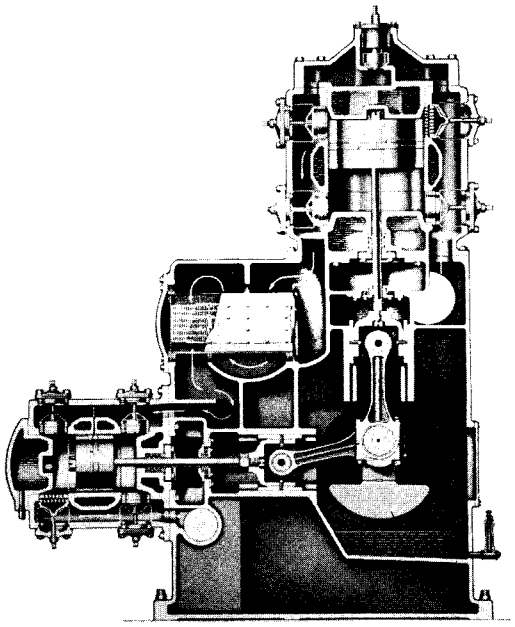



### Free-Piston Compressors

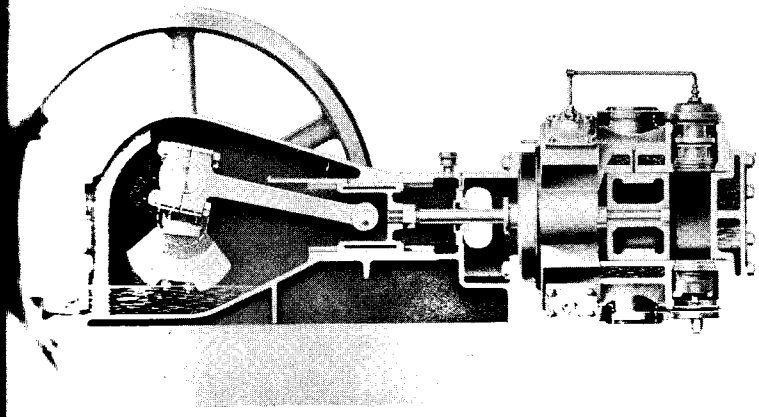
These compact, relatively vibration-free units now find commercial use in Europe. Diagram shows one arrangement, with opposed-piston diesel cylinder in center, air cylinder at ends. For details, see POWER, Feb 1951, pp 84-86.



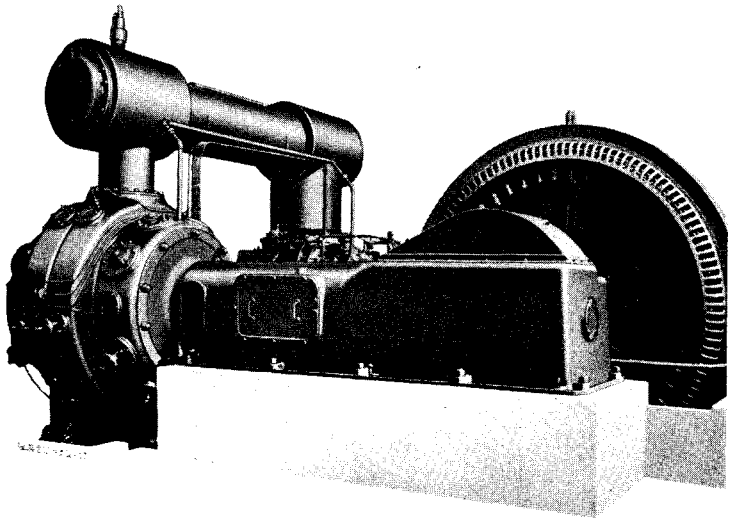
2 "Package-type" compressor has components on a single base for easy mounting directly on plant floor, is water-cooled



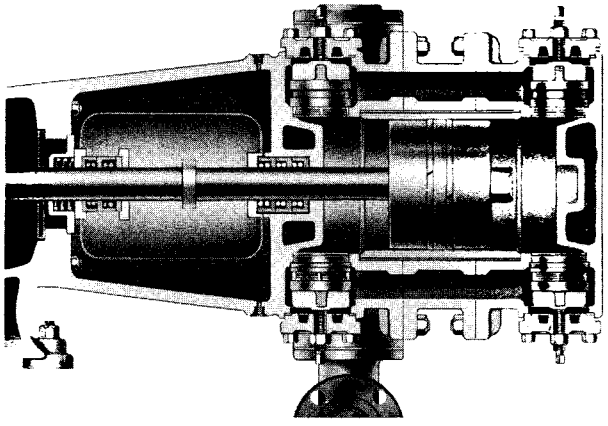
3 Another package-type compressor has its cylinders at right angles, takes little space. Water-cooled, 2-stage, 350-hp



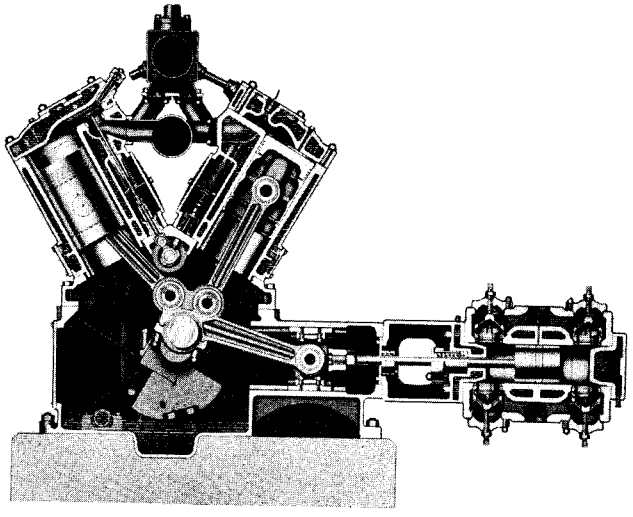
5 Horizontal single-frame units like this are built in wide range of capacities. Normal pressure rating is 100 psi



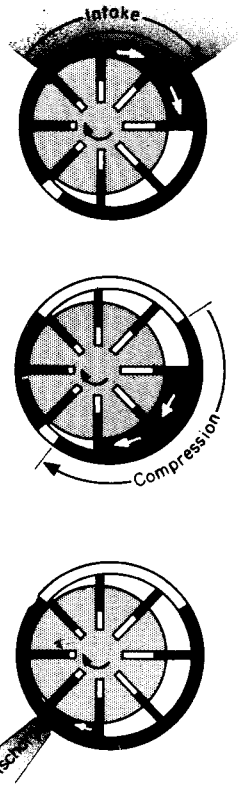
6 Duplex double-acting compressor is typical of designs in this type for 80 to 125 psi. Made in wide capacity range



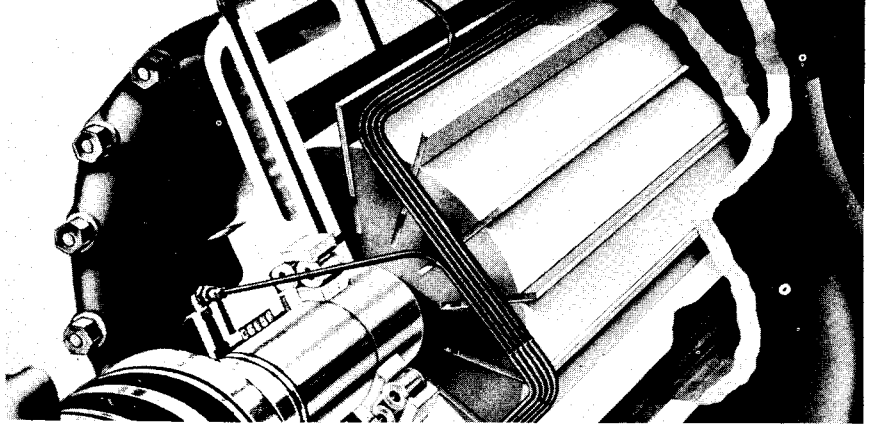
8 Oilless compressor uses no lubricant in cylinder, discharges oil-free air. Cylinder liner is carbon, backed with steel



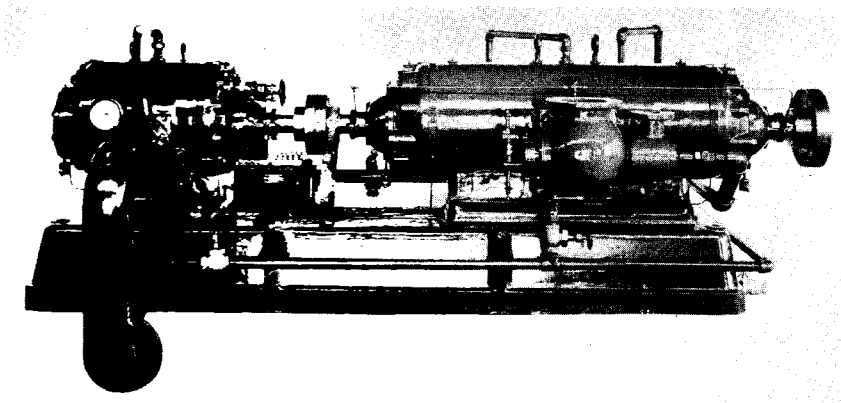
9 This V-type gas engine drives horizontal air compressor; two units are combined in a single frame for compactness




**SLIDING-VANE** design traps air between vanes, compresses by reducing volume



**CUTAWAY VIEW** of a sliding-vane rotary compressor showing water-jacketed cylinder, rotor with axis eccentric to that of cylinder, vanes that move radially in slots



**TYPICAL SLIDING-VANE COMPRESSOR** has three points in cylinder, one in each head, that get oil from force-feed lubricator driven from either motor or compressor shaft

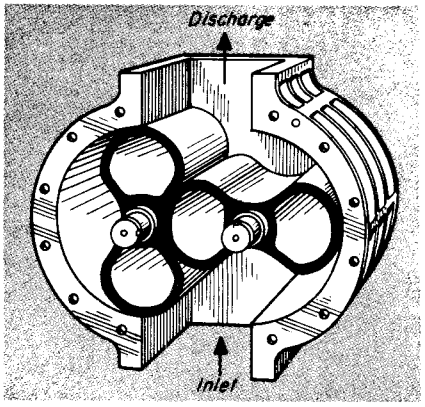
# Rotaries

Rotary compressors, as we saw earlier, are positive-displacement units. Diagram, *above,* shows events in one revolution of a sliding-vane unit. Depending on design, cooling may be with atmospheric air, oil or water. For pressures to 50 psi, one stage is used, two stages for higher pressures. Capacities range to about 5000 cfm.

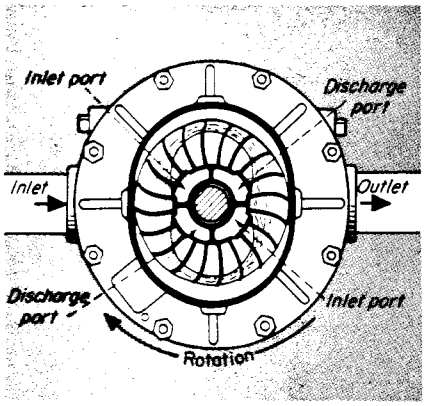
Some compressors of this type have rings around the vanes to keep them from bearing on cylinder walls. Others have vanes bearing against cylinder.

**Lobe Types.** Two- and three-element positive-displacement designs, *right,* have capacities from 5 to about 50,000 cfm. Pressures above about 15 psi are obtained by operating two or more units in series. Impellers are straight, as shown, or slightly twisted.

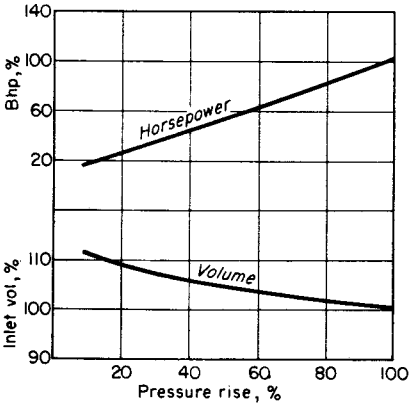
**Liquid-piston** compressors, *right,* handle up to about 5000 cfm. Single-stage units can develop pressures to 75 psi; multistage designs are used for higher pressures. Water or almost any other low-viscosity liquid serves as the compressant. For exacting services, compressor may be sealed with chilled water to prevent condensation in lines.



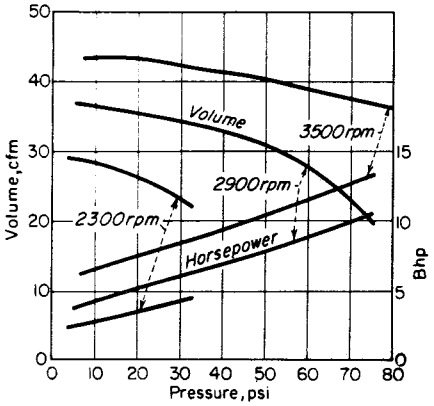

**TWO-LOBED** impellers rotate in opposite directions, carrying the air with them




**LIQUID-PISTON** unit has shrouded vanes rotating in casing, no metallic contact

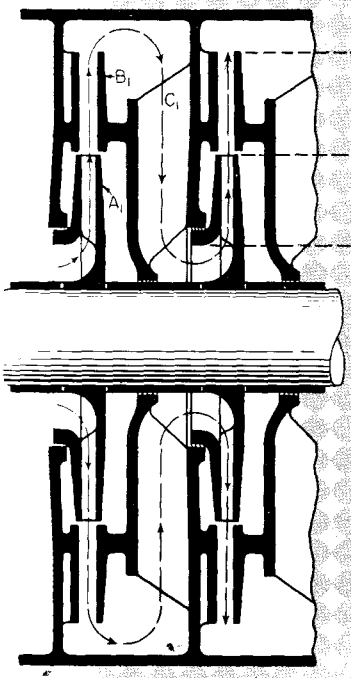



**CHARACTERISTIC** curves for a constant-speed two-impeller-type air compressor

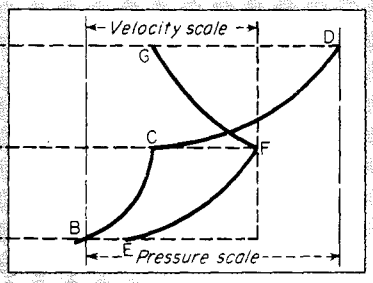



**TYPICAL PERFORMANCE** curves for single-stage liquid-piston unit show power, cfm

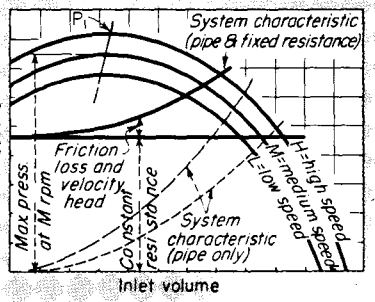
# Centrifugal Compressors Can Supply Large Volumes of Air



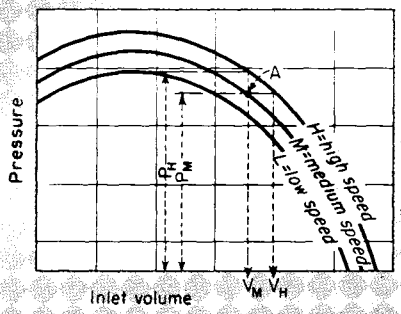

AIR FLOW through centrifugal compressor follows paths shown in this drawing



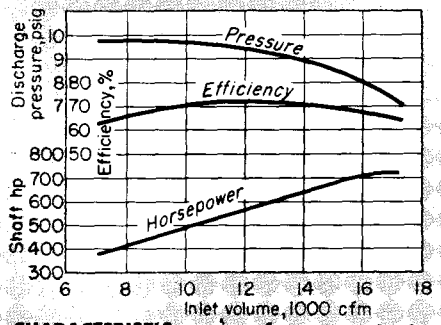

**PRESSURE and velocity relationships of air in a typical centrifugal compressor**




**OPERATING FACTORS governing the action of a centrifugal at a fixed load**




**VOLUME and pressure relationships of a centrifugal compressor at various speeds**




**CHARACTERISTIC curves for a constant-speed machine driven by electric motor**

# Centrifugals

In centrifugal compressors, air travels essentially radially. Look at the section above and the related diagram in which pressure and velocity are plotted against radial travel.

**How Centrifugals Work.** Centrifugal action of impeller produces some pressure rise ($BC$) and a big increase in air velocity ($EF$). In the diffuser ($B_1$ in section), velocity energy is converted to static pressure. Velocity falls from $F$ to $G$, pressure rises from $C$ to $D$.

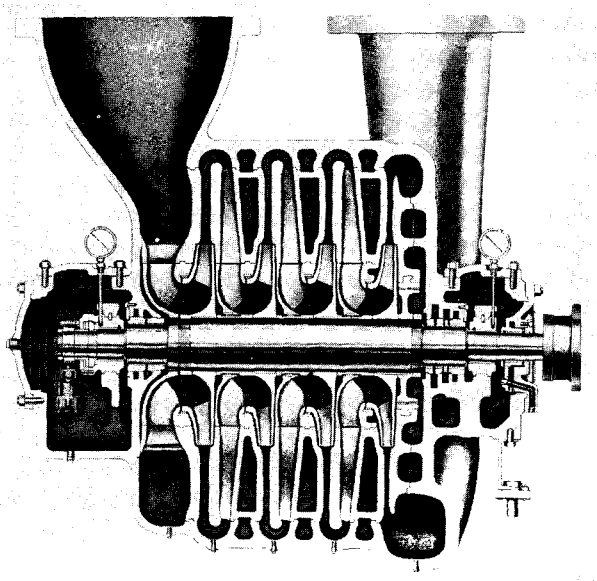
Pressure-volume curves for centrifugal compressors resemble those shown, *above center*. Each curve is for a different compressor speed. Unit running at speed $M$ delivers volume $V_M$ at pressure $P_M$ (point $A$). Increasing speed to $H$ raises volume to $V_H$ at $P_M$ or old volume $V_M$ can be delivered at higher pressure $P_H$.

Curves, *top right*, show how compressor runs when discharging through a pipe to a system with constant resistance, and through pipes only. If discharge pressure falls below $P_1$, operation may be unstable.

Pressure delivered by a centrifugal is practically constant over a relatively wide range of capacities. As a close approximation you can consider shaft hp to vary as the cube of compressor operating speed if characteristics of system into which unit discharges are held constant.

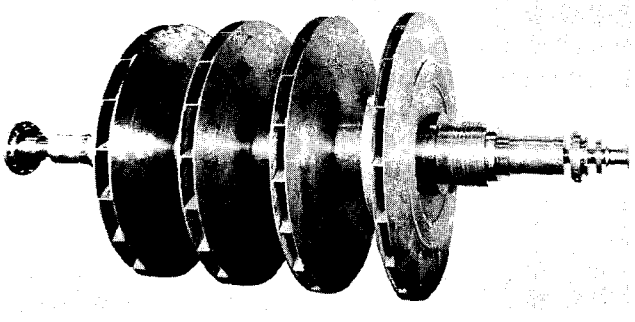
**Pumping limit,** also called surge point or pulsation point, is lower limit of stable operation. Percentage stability is 100 minus the pumping limit in percent of design capacity.

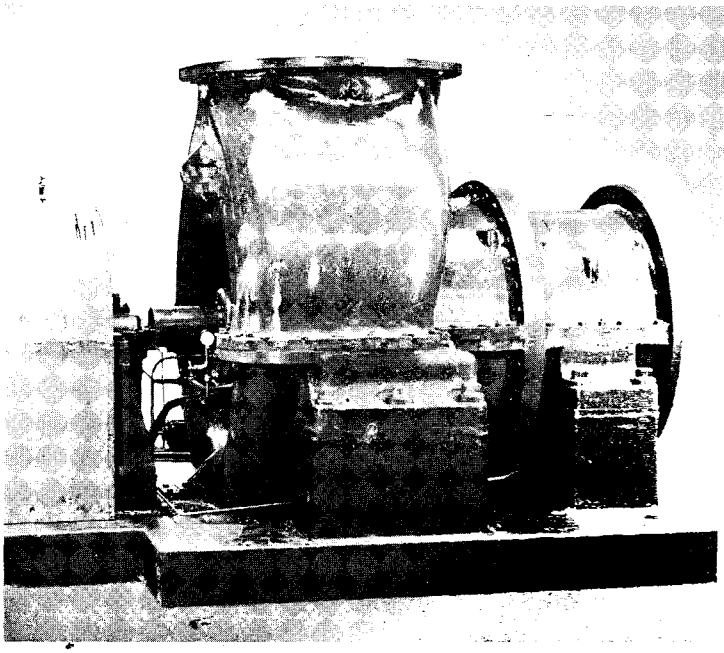
Multistage centrifugal compressors handle 500 to more than 150,000 cfm, at pressures to 150 psi. For pressures under about 35 psi, centrifugal units are usually classified as blowers. Except in smaller sizes there is little mechanical difference between blowers and compressors.



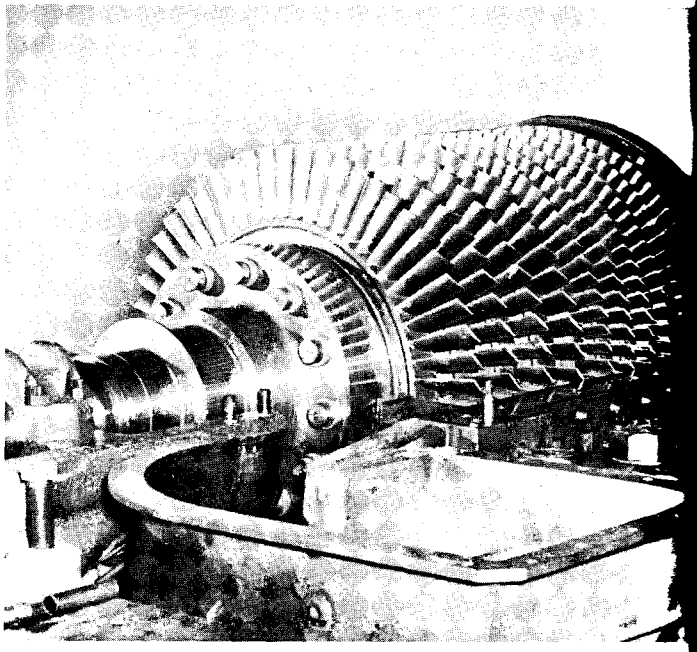
**LONGITUDINAL SECTION of 4-stage centrifugal suitable for supplying large quantities of air. Discharge pressure to 150 psi**

**ROTOR for typical multistage centrifugal compressor. Impellers are of enclosed (fully shrouded) single-suction design**

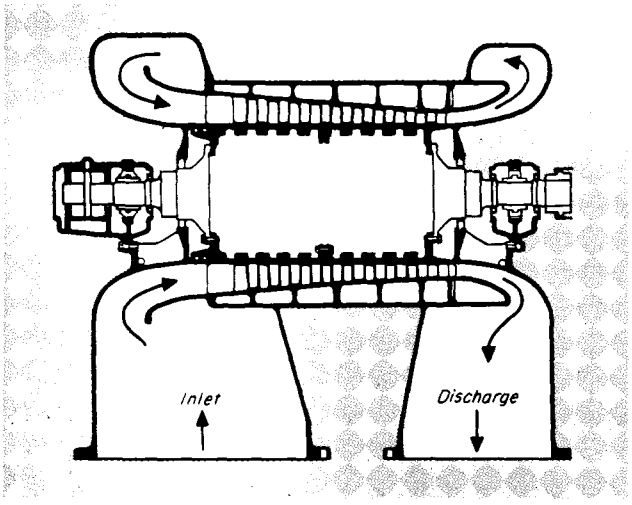




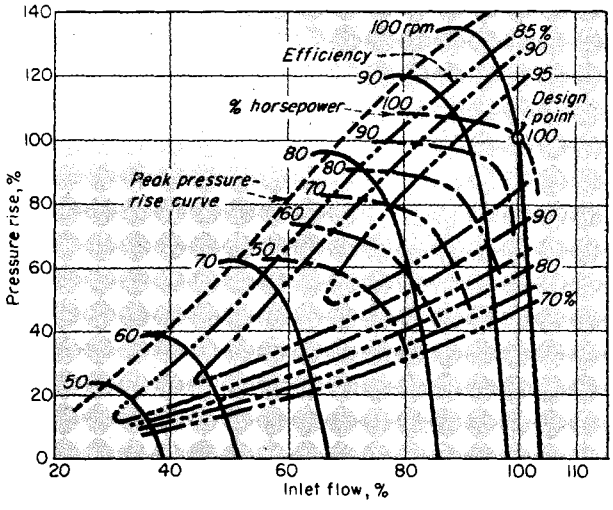
**TURBINE-DRIVEN** large-volume low-pressure axial compressor. Four-stage, it handles 50,000 cfm. Note axial inlet at right



**ASSEMBLY** of an 11,000-hp axial-flow air compressor designed to handle large volumes of air. Note construction of the rotor




**CROSS SECTION** of an axial-flow compressor suitable for handling large quantities of air. Note straight-through flow path




**PRESSURE-VOLUME** characteristic of axials is steep, making them well suited to fixed-volume large-pressure-change jobs

# Axial-Flow

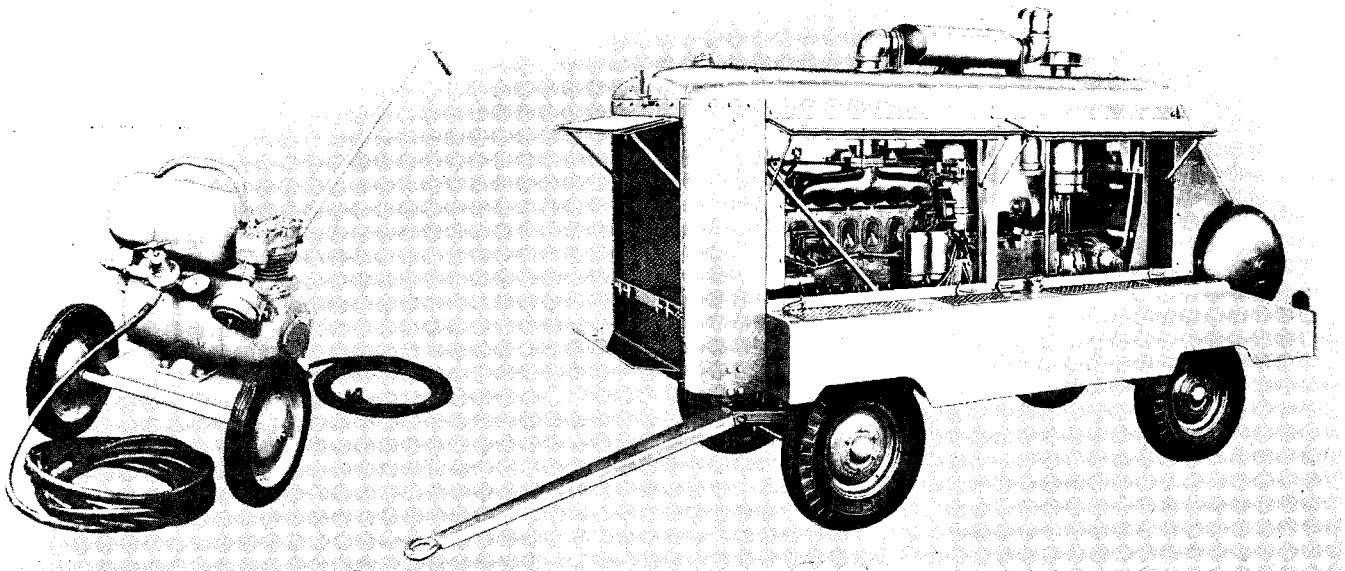
In axial-flow compressors, air moves generally parallel to the shaft axis, *diagram above*. Single-stage axial blowers have capacities from a few cfm to more than 100,000, at pressures from less than one to several psi. Multistage axials compress air to 150 psi or more. Some special machines handle over one million cfm. Pressure rise per stage is generally relatively small so units for higher pressures frequently have a considerable number of stages.

While centrifugal machines deliver practically constant pressure over a considerable range of capacities, axials have a substantially constant delivery at variable pressures. In general, centrifugals have a wider stable operating range than axials.

Because of their more or less straight-through flow, axials tend to be smaller in diameter than centrifugals, and are apt to be longer. Efficiency of axials usually runs slightly higher.

To prevent surging at extremely low loads, large-capacity axials are sometimes fitted with a blowoff system that discharges excess air to the atmosphere. With this hookup there is always enough air passing through the machine to keep it in stable range.

Because of difficulty in accurately predicting the characteristic curves of centrifugal and axial compressors, only one capacity and one discharge-pressure rating, together with corresponding power input, are normally guaranteed. Shape of the characteristic curve may be indicated but is never guaranteed.



**MOTOR-DRIVEN** portable design for plant maintenance work supplies 150-psi air

**PORTABLE COMPRESSOR** rated 600 cfm is a 2-stage diesel-driven sliding-vane rotary. Light, compact, it is easily towed

# Portables

Portable compressors find ever wider use in industrial plants for maintenance, spray painting, filter cleaning, tire inflating, and many other tasks. Smaller units are easily moved about by one or two men for spot jobs of all kinds. Having portables on hand prevents overloading the main air system when a lot of maintenance work must be done or other peaks occur. And, of course, portables are still the old standby in all types of industrial construction.

Completely self-contained, portables may be skid-, truck- or tractor-mounted, or may have two or four wheels, with or without springs and tires.

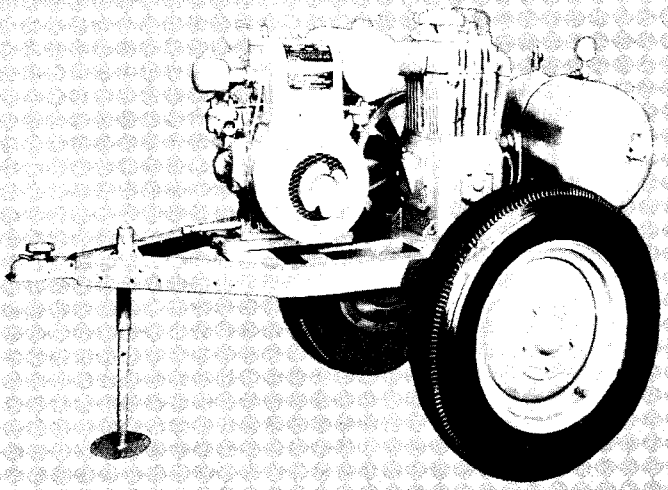
**Standard portables** are rated for 100-psi discharge pressure at sea level. Sizes are stated in model numbers, corresponding to compressor capacity in cfm of free air delivered at 100 psi at sea level. *Model 60*, for instance, is rated at 60 cfm, *Model 105* at 105 cfm, *Model 600* at 600 cfm. Maximum standard capacity is 600 cfm.

Most portables available today are reciprocating units, driven by either gasoline or diesel engines. One type, however, uses a 2-stage sliding-vane rotary compressor. Portables designed specifically for in-plant use may be driven by gasoline, diesel engines or electric motors, whichever works out best for a given plant.

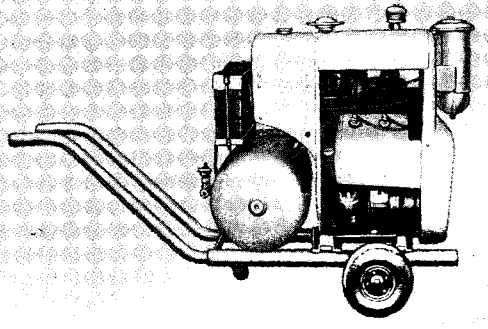
**Self-propelled compressors,** of the tractor type, may prove more useful than straight portables in large industrial plants. Many different auxiliary parts can be fitted to them. These include a snow plow, front-end loader, rotary brush, rear winch, booms of different lengths, post-hole digger, lawn mower, portable scaffold, earth auger, back hoe, and other useful devices.

Similar units are also available in crawler designs with steel tracks for towing, climbing or pushing, besides supplying compressed air. Standard model numbers for portables apply to self-propelled units, too.

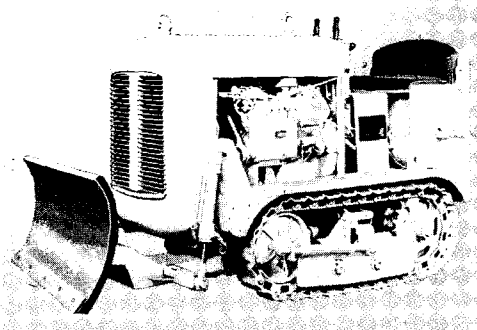
All present-day designs of portables and self-propelled units include compressor, prime mover, and air receiver, complete with cooling, lube, regulating and starting systems.



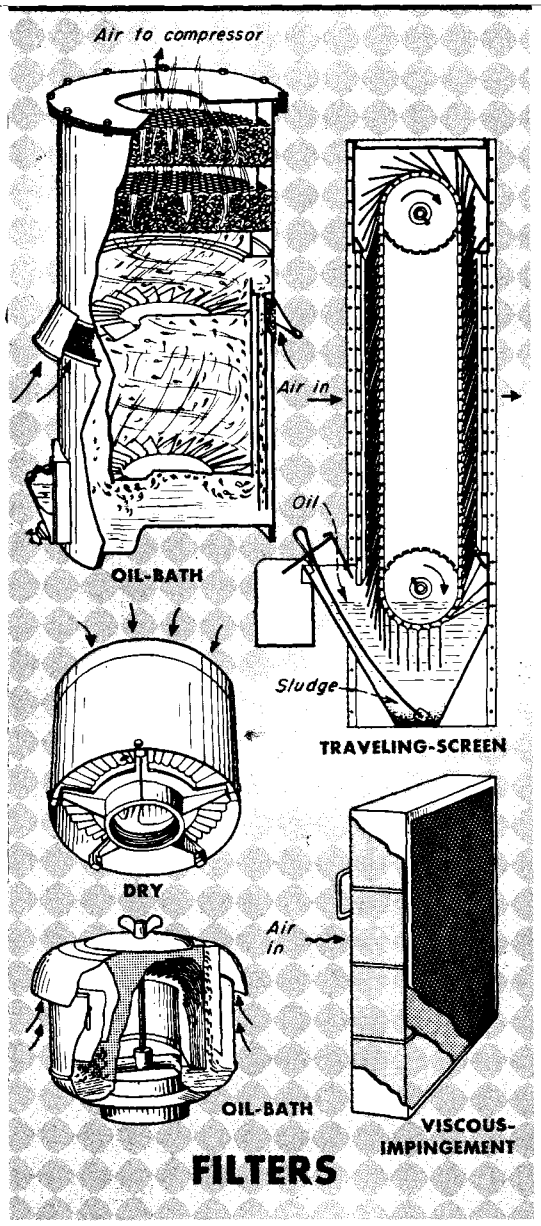
**TRAILER-MOUNTED** portable, single-stage air-cooled for 70-80 psi. Drive is gasoline engine (or motor)

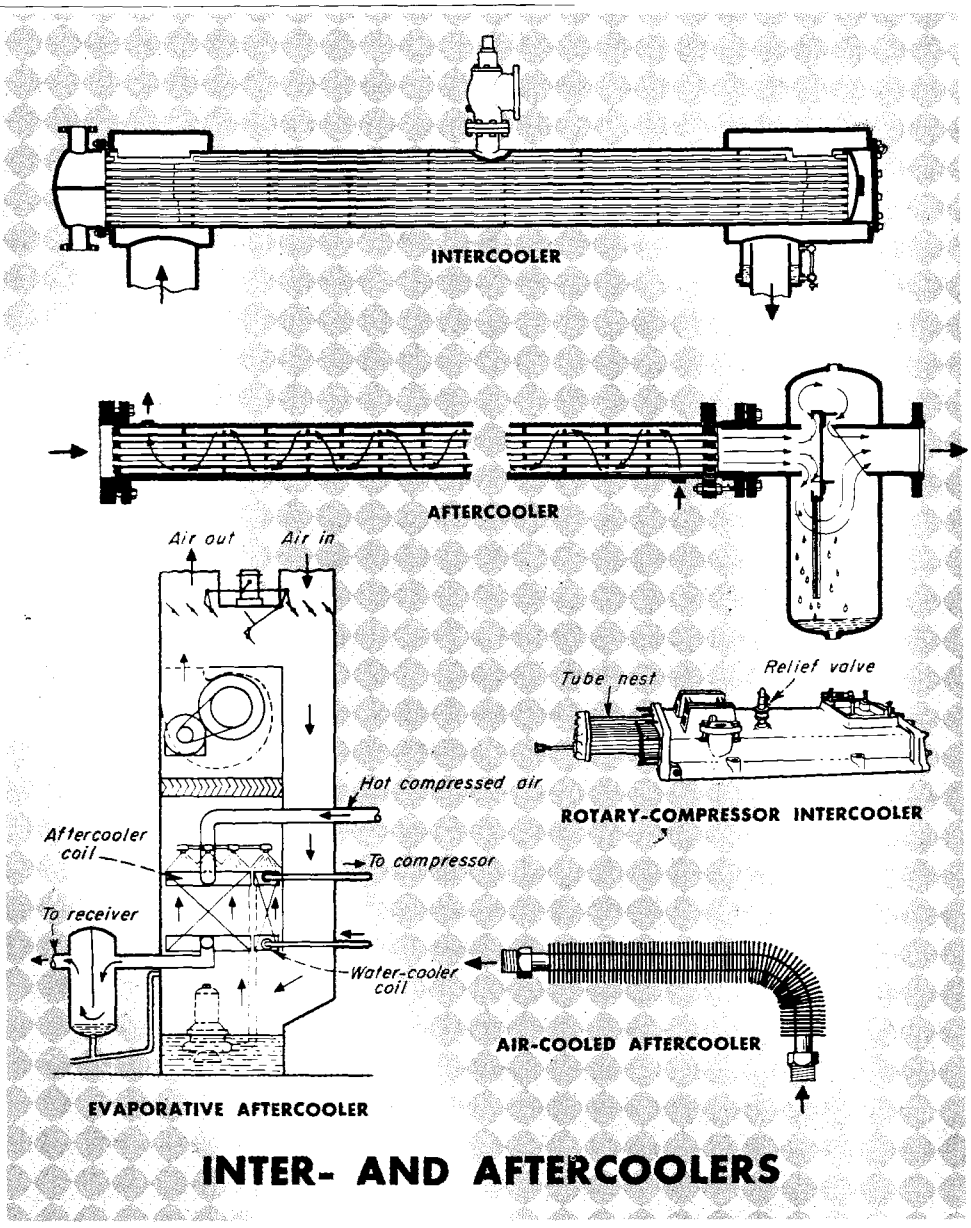


**LOW-SLUNG** shop truck has two pneumatic-tired wheels and a caster wheel, is easily hauled around



**CRAWLER-TYPE** self-propelled compressor can be fitted with many tools, is useful in large industrial plants




# Compressor Accessories

Heart of any air system is the compressor, but a number of auxiliary devices are needed. Some, like inter- and aftercoolers, may come as part of the compressor; others, like separators, are accessories, usually come separately.

**Intake-air filters** prevent dust and other atmospheric impurities from entering compressor. Dust, for example, may cause sticking valves, scored cylinders, excessive wear.

Sketches, *above left,* show several typical filter designs. *Viscous-impingement* types—rectangular or cylindrical—are packed with fine strands of wire coated with oil. Air passing through impinges on wires, oil film traps dust. *Oil-bath filters* have a reservoir of oil agitated by incoming air. Oil-coated dust collects in oil reservoir.

In *traveling-screen filters,* air flows through a screen continuously coated with oil by passage through a reservoir. Dust caught on screen is washed off in oil bath.

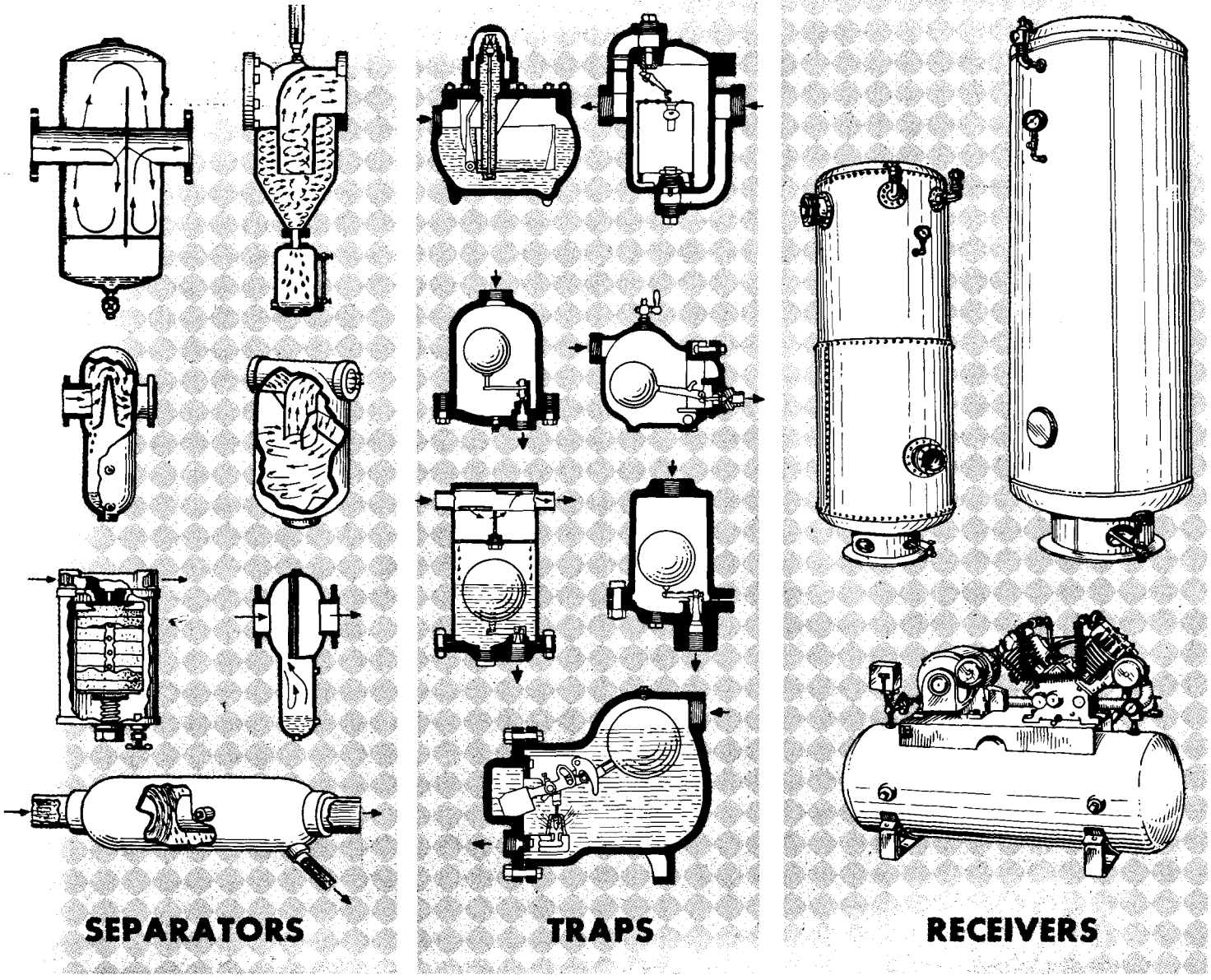
*Dry-type* filters have felt or other filtering media held in rectangular or cylindrical frames. Some types of filtering materials may be vacuum cleaned, others are designed to be used just once, in *throwaway* elements.

**Inter- and Aftercoolers.** Atmospheric air, as we saw earlier (p 86), contains moisture. And in passing through compressor, air may pick up atomized oil. So discharge air usually carries water and oil vapor, and is at an elevated temperature as a result of the compression process.

Water that reaches air tools may wash away lubricant, causing excessive wear. It may also reduce pipe capacity by collecting at low points, where it may freeze in cold weather. Water hammer may also be a problem.

Oil in air can damage rubber gaskets and air hoses, plug discharge piping if it carbonizes. It's objectionable in some jobs—paint spraying, cleaning of electrical equipment, agitation of liquids.

One way of removing water and oil vapor is to cool air. When done between stages in a multistage compressor, an *intercooler* is used. It may be either a water-cooled shell-and-tube unit for large compressors or a finned-tube air-cooled type for small units. Water and oil are often collected in a trap at cooler's discharge end. Gage glass shows water level and a drain connection is provided. Besides removing




unwanted vapors, intercooling also reduces power input to compressor—see p 86 for details.

*Aftercoolers* reduce temperature and moisture content of air leaving the compressor's last stage. These may be water- or air-cooled, like intercoolers. Evaporative aftercoolers cool both air and compressor cooling water.

Sketches, *above,* show several typical designs of aftercoolers. Many water-cooled units incorporate a separator. Temperature of air leaving cooler is usually within 2 to 15 F of cooling water. In some plants today, chilled water is used for maximum vapor removal. For drying air to be used in pneumatic instruments, silica gel, alumina or other adsorbents may be used. These are reactivated by heating after they become saturated.

**Separators.** Because aftercoolers remove moisture and oil only in proportion to their ability to lower air temperature, separators are generally used between aftercooler and receiver. They are also used in branch lines where there is danger of condensation, or where tools or devices served need protection of an additional separator.

Sketches, *above,* show only a few of the many separator designs in use today. Some utilize centrifugal force or a sudden change in flow direction to throw out moisture particles. Others employ rotating impellers, felt disks, porous stone cups or disks to separate moisture. One design has a water-cooled condenser in the separator body.

**Traps,** *above center,* are often used at separators, drain pockets and in tool lines to discharge condensed moisture. Since much air may be lost through traps discharging continuously, and since condensation in air lines is not as rapid as in steam lines, intermittent-discharge traps are usually recommended for air service.

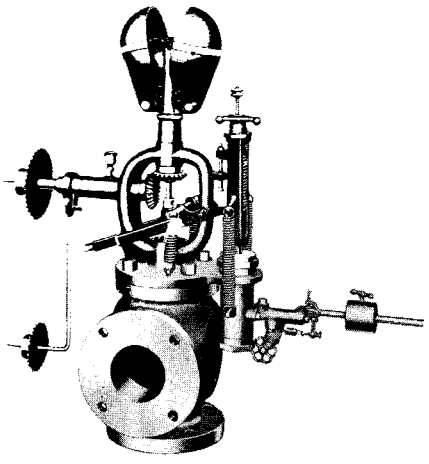
Air traps closely resemble those for steam service, inverted-bucket, upright-bucket and float types being among those used. Traps discharge oil as well as condensed water. Of many designs a few are illustrated above.

**Receivers** dampen pulsations or pressure waves in compressor discharge, act as reservoirs and precipitate any moisture that may be carried over from aftercooler.

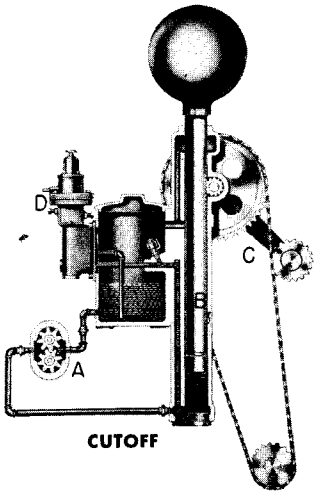
Large receivers are usually vertical, *above right.* Small ones may be horizontal or vertical, depending on space available. Many states require that air receivers conform with ASME code for unfired pressure vessels. Receivers built in accordance with code are standard size, fitted with openings for inspection and cleaning, plugged opening for a regulator, and with safety valve, pressure gage and drain valve. Construction may be either welded or riveted. Metal mounting base is usually furnished with receiver.

**Silencers** are available for installations where compressor inlet or discharge noise is objectionable.

**Protective devices** for compressors take a variety of forms. Typical ones are listed and discussed on p 103.

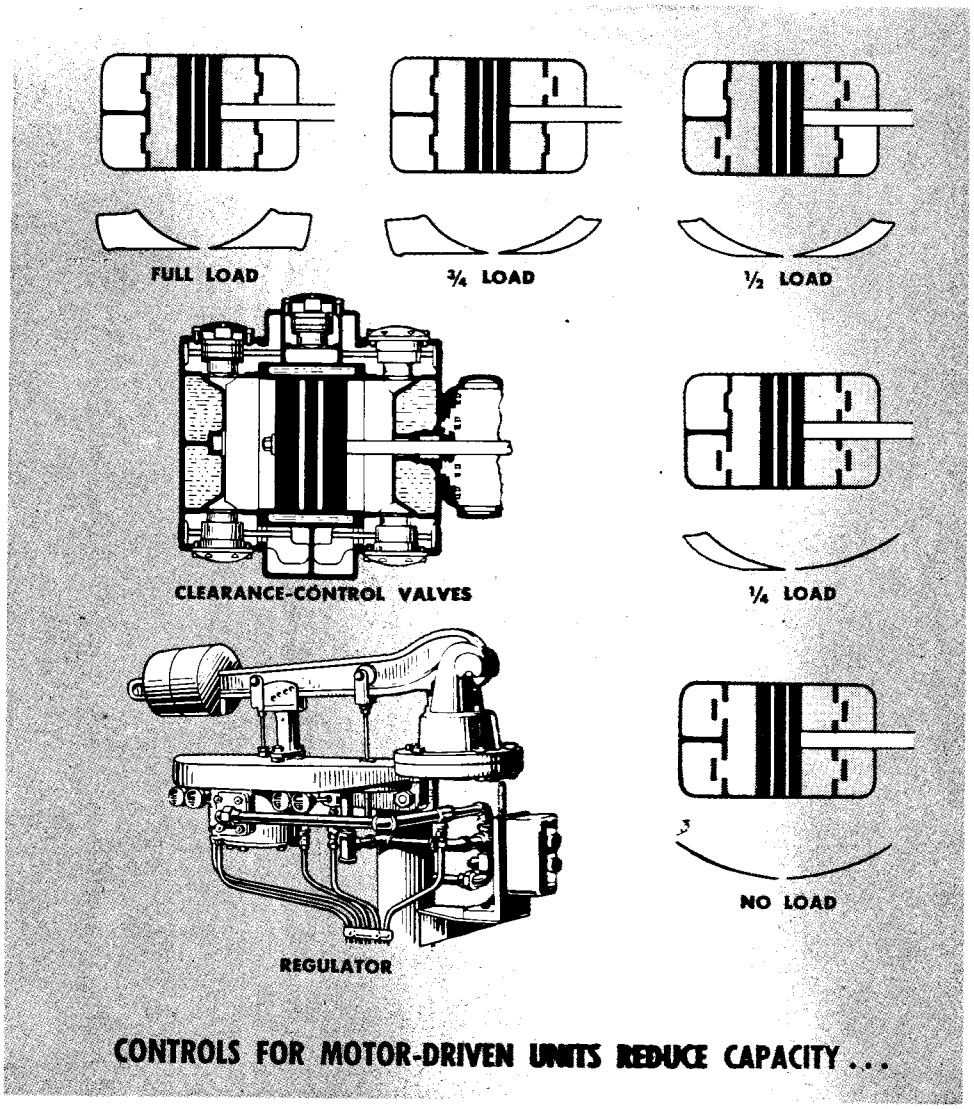


THROTTLING




CUTOFF

**STEAM-ENGINE GOVERNORS**




**CONTROLS FOR MOTOR-DRIVEN UNITS REDUCE CAPACITY . . .**

# Control

Compressor controls permit you to regulate output to load. For reciprocating units, type depends on drive, nature of load and other factors.

**Steam-driven** compressors usually have combination speed and pressure governors that vary air capacity by changing speed. They are available in two types: (1) *Throttling* governors vary steam pressure, reducing it as air-discharge pressure rises. (2) *Automatic-cutoff* governors change cutoff point of valves in steam cylinder.

Throttling design, *top left,* is used with manually adjustable cutoff in plants having steady supply of exhaust steam or where conditions are so nearly constant an automatic-cutoff governor would have little chance to function. Cutoff is set manually at desired point, governor holds constant air pressure by varying machine speed.

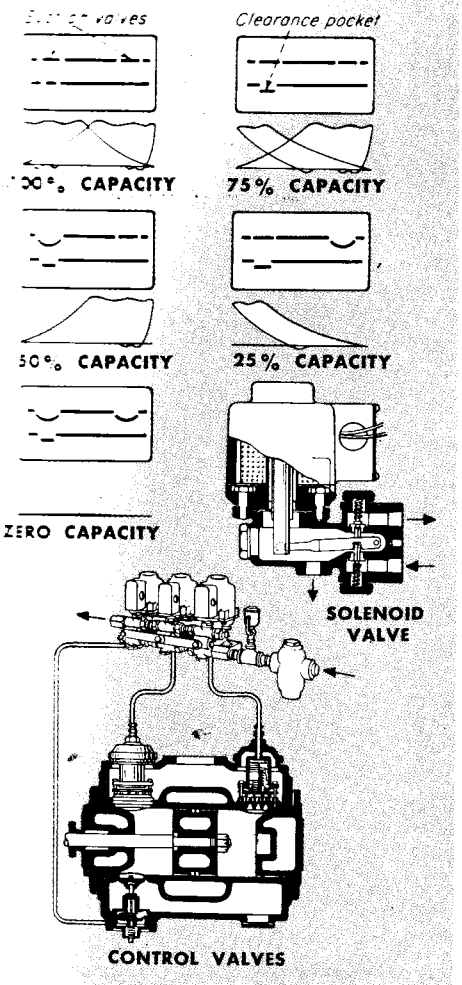
One design of automatic-cutoff governor, *above left,* has a gear-type oil pump, *A,* chain-driven from main shaft. Oil under pressure from pump acts on piston *B.* Any steam-pressure change tending to shift compressor speed is instantly reflected in an increase or decrease of oil pressure. This causes piston movement, which rotates sprocket combination *C* to reset cutoff and restore required speed. Variations in air demand acting through diaphragm valve *D* (connected to receiver) also affect oil pressure by permitting some oil to bypass. In these two ways, speed is controlled according to load demand and steam conditions.

**Motor-driven** and other types of constant-speed compressors usually have one of three types of controls: (1) Constant-speed control decreases compressor capacity automatically in one or more steps by means of an unloader. (2) Automatic start-and-stop control uses a starter and pressure switch. This control works well where air demand is intermittent with long periods of no demand and where precise pressure regulation is unnecessary. (3) Dual control is a combination of (1) and (2). It allows continuous operation when demand is nearly continuous, and automatic start-and-stop when demand is low.

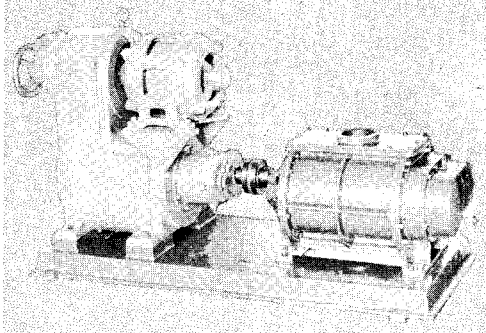
**Step Control.** Two designs of constant-speed 5-step control are shown above. Each unloads compressor in five steps, reducing capacity from full load to ¾, ½, ¼ and no load as demand decreases. Five-step control is almost universal on compressors of 150 hp or more. Many smaller compressors have 3-step controls. Most single-acting units (15 to 125 hp) have 1-step control for unloading.

With one type of 5-step control, above, each end of each cylinder has two clearance pockets fitted with an air-operated clearance valve opening into the cylinder bore. When one valve is open, pocket volume is added to normal clearance volume. This reduces intake-air quantity to half that normally taken in by that end of cylinder. Pocket size is proportioned so when both pockets at one end are open, no air is taken into that end of cylinder when operating at rated pressure.

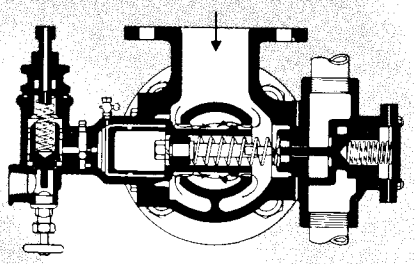
Regulator for 5-step control has a diaphragm connected to receiver pres-



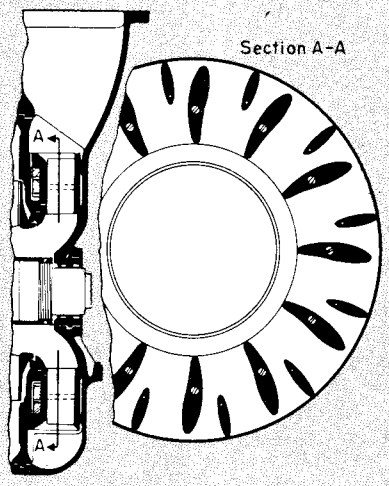

... IN FIVE STEPS OR LESS



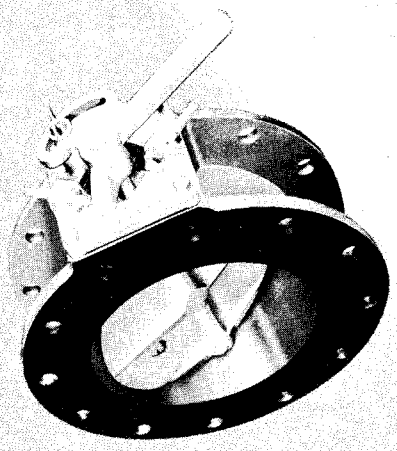
VARIABLE-SPEED DRIVE



INTAKE UNLOADER FOR SLIDING-VANE COMPRESSOR




ADJUSTABLE INLET-GUIDE VANES



HAND-OPERATED BUTTERFLY VALVE

SOME CONTROLS FOR ROTATING COMPRESSORS

sure to operate a pilot valve. This causes auxiliary valves to open and close to admit and exhaust pressure from clearance-control valves.

**Suction valves** as well as clearance pockets are used in the 5-step control, *directly above*. Hookup is for a 2-stage 2-cylinder unit having one clearance pocket in each cylinder and an arrangement for unloading low- and high-pressure cylinders simultaneously.

Three solenoid valves control admission of air pressure to unloading elements. De-energizing the solenoids admits pressure for unloading. Energizing solenoids removes pressure from unloader, allowing compressor to load and discharge air. Automatic initial unloading, or unloading during abnormal electrical conditions, is obtained by interlocking the solenoid-valve circuit with the motor starter.

Energizing or de-energizing of solenoids in proper sequence (diagram) is under governor control.

Similar 5-step control for 2-cylinder single-stage compressors without clearance pockets unloads each end of each cylinder in sequence.

**Automatic start-and-stop** controls have a simple pressure-actuated switch connected to the receiver. Range between starting and stopping pressures is usually about 20% of cutout pressure. Pressure-release valve automatically bleeds or unloads compressor, permitting it to start against no load.

**Dual-control** schemes have a manually operated switch for changing from automatic start-and-stop to constant-speed control. They prove most economical in plants with heavy and light demand periods.

**Rotary compressors** may be controlled by varying speed, by unloading, or by the dual method. Illustrated above is an automatic intake unloader for a sliding-vane unit.

Pressure developed in some types of rotaries depends on system resistance. Since most units are designed for a specified maximum pressure differential, a relief valve is needed on discharge to protect against an excessive discharge pressure.

**Centrifugal compressors** are controlled by three methods: (1) variable speed (2) movable internal vanes (3) suction or discharge throttling.

Variable-speed control is efficient and widely used. It is obtained directly with turbines, wound-rotor or dc motors. Hydraulic or magnetic couplings, or some other variable-speed drive, are needed with squirrel-cage induction or synchronous motors.

Inlet-guide vanes, at first impeller or at each impeller, can be used to modify the performance characteristics of centrifugals. Such vanes may be made manually adjustable or, in some cases, automatically adjustable.

Suction or discharge throttling is the least efficient control method. Butterfly valve in inlet line artificially reduces inlet pressure to change output. Or butterfly in discharge reduces compressor outlet pressure. Inlet throttling is more efficient, finds greater use.

**Axial-flow-compressor** control depends on application. One type, for example, regulates driving-turbine speed to maintain constant air flow. Discharge side of system has separately controlled blowoff valve for unusual operating conditions that take compressor out of its stable range.

# Compressor Selection

Up to this point, the compressors and accessories we've covered have not been classified for ultimate use. But since most power engineers handle so called "shop" air systems, we'll concentrate on these familiar plant hookups from here on.

## Compressor Size

Compressor selection takes experience and judgment, but there are some guides that often prove helpful. To show how you can use them, we'll set up a typical compressor-selection problem and solve it. But remember, every time you pick a compressor you should have the maker check your figures from start to finish.

**First step** in compressor selection is determination of air quantity needed and top pressure to operate any air device in the plant. Table I gives consumption of a number of typical air tools. You can use these figures for a first estimate, or obtain exact values from tool manufacturers.

Most air tools are designed for operation at 90 psi. Unless maker specifically states otherwise, tool performance figures and capacity ratings are based on an air supply providing 90 psi *at the tool* when it's being used.

Assume our plant is a new one and will use tools listed above. Beside each tool put its average air consumption in cfm (column *a*). Obtain this from tool manufacturer or Table I. Tabulate in column *b* the number of tools of each type. Then multiply columns *a* and *b* to find total air consumption of each type of tool, column *c*.

**Load Factor.** Few air tools operate continuously. As a result, their *net* air consumption is usually less than the *average* value stated by the maker or listed in Table I. Ratio of actual air consumption to that for full-load continuous operation is called *load factor.*

Two items are involved in load factor. First is the *time factor,* or percent of total time the tool or device actually uses air. Second is *work factor,* or percent of maximum possible work output actually done by the tool. For example, air consumption of a grinder with wide-open throttle depends on how hard operator pushes it against the work. Load factor is thus the product of time and work factors.

As you see, load factor is extremely important in compressor selection. For a given tool, load factor can normally vary from 0 to 100%, depending on tool type, its use, production rate, operator's habits, etc.

**Best way** to determine load factors for a new plant is by consulting the tool makers. In a plant that's been operating for some time you can use past experience as a guide, plus data from tool manufacturers. Just be certain that load factors you choose represent usual procedure in your plant. Enter factors in column *d,* as shown. Note: Tabulated values apply only to this example and should not be taken as representative. Each plant is different and load factors vary considerably.

Multiply value in column *c* by that in *d* for each tool. Result, column *e,* is average air demand of each group of tools. Add the results in *e* to get total average demand of all tools in plant. This sum is a rough indication of compressor capacity needed if it includes only tools normally used and omits those stored in toolrooms or out of service for other reasons.

**Leakage.** Some plant designers add an arbitrary item of 10% for piping and tool leakage. This practice isn't approved by the Compressed Air and Gas Institute. They recommend tight piping and good tool maintenance instead.

Remember, compressed-air usage tends to increase in most plants. If you expect system load to increase soon, insert a factor so the compressor you buy can handle new loads. It is usually more economical to provide additional capacity at start than later.

### Typical Computation of Compressed-Air Requirements

| Tool | (a) Air consumption, cfm | (b) Number of tools | (c) Air req'd, cfm (a x b) | (d) Load factor | (e) Probable air demand, cfm (c x d) |
|---|---|---|---|---|---|
| Grinding wheel, 6 in. | 50 | 5 | 250 | 0.3 | 75 |
| Rotary sander, 9-in. pad | 55 | 2 | 110 | 0.5 | 55 |
| Chipping hammers, 13 lb | 30 | 8 | 240 | 0.4 | 96 |
| Nut setters, 5/16 in. | 20 | 10 | 200 | 0.6 | 120 |
| Paint spray | 10 | 1 | 10 | 0.1 | 1 |
| Plug drills | 40 | 3 | 120 | 0.2 | 24 |
| Riveters, 18 lb | 35 | 5 | 175 | 0.4 | 70 |
| Steel drill, 7/8 in., 25 lb | 80 | 5 | 400 | 0.4 | 160 |
| | | | | | 601* |

*To this value must be added allowance for future needs and expected leakage loss, if any.

## Special Needs

Where compressors supply air for services other than tools, you must consider some other angles. For instance, air for pneumatic instruments must be absolutely clean and oil-free. Also, it may be needed at a lower pressure than for tools—often in the 20-psi range. So we find liquid-piston, lobe, sliding vane and oilless compressors, popular for this service.

Compressors for soot blowing come at the higher end of the pressure scale, with a discharge pressure of 500 psi common in some plants. By storing air in receivers at 500 psi and reducing to 250 psi before use, a smaller compressor can be installed.

Some of the compressors discussed earlier find use in industrial vacuum service with little or no change. Under these conditions, intake pressure is below atmospheric, discharge is atmospheric or slightly above.

Your best bet on all applications, specialized or not, is to work closely with the compressor maker. His long experience assures you that the unit he recommends will give good service.

**Drive.** Motors, gas, gasoline, diesel, steam engines, or turbines are used to drive air compressors. Choice of drive is a matter of economics, involving

fuel cost, availability, cost of electricity, chance of electrical outages, availability of steam and a number of other factors. Plants needing more than one compressor may benefit by using a motor on one, prime movers on others.

Figures in Tables II-V help in making an economic analysis. Note the bases on which they're calculated and adjust if your conditions differ. Be sure to have compressor manufacturer check your choice of drive to see if it is entirely suitable for your plant.

## Compressor Type

Compressed Air and Gas Institute gives the following relations between pressure and number of stages: 0-150 psig, single stage; 80-500 psig, two; 500-2500 psig, three; 2500-5000 psig, four stages. These ranges are for usual positive-displacement units.

**Before choosing** a specific type of compressor you must consider a number of factors including: discharge pressure required, capacity needed, power-supply characteristics, availability and cost of cooling water, space needed for compressor, type of control desired, compressor weight, type and size of foundation, and amount of maintenance expected.

Use the general ranges above to give a rough indication of number of stages for positive-displacement units. Send a complete picture of your air requirements to several manufacturers for their recommendations on type and size of compressor that is best for your plant and its load.

**Never overlook** the help you can get from manufacturers when it comes to picking a compressor. They will gladly give you estimated operating costs for different service conditions, drives, cooling arrangements, etc. Remember, the average life of a compressor is usually 20 years or more. So every decision you make that affects the operating cost will be with you for a long time.

Details given earlier, pp 88-95, help you choose between the two basic types — positive displacement and dynamic. Once this decision is made you can make a further study of the characteristics of various compressor types to see which one will be best for your job. Just remember that the selection of a compressor is an engineering decision that should take every factor into consideration.

**Efficiency.** One good measure of compressor efficiency is bhp per cfm. While efficiency is always important, especially when load factor and power cost are high, air pressure at tools is just as important. We'll take a look at this on the next two pages.

## I—Approximate Air Needs of Pneumatic Tools, Cfm

| | |
|---|---|
| Grinders, 6- and 8-in. diameter wheels | 50 |
| 2- and 2½-in. diameter wheels | 14-20 |
| File and burr machines | 18 |
| Rotary sanders, 9-in. diameter pads | 55 |
| Sand rammers and tampers: | |
| 1x4-in. cylinder | 25 |
| 1¼x5-in. cylinder | 28 |
| 1½x6-in. cylinder | 39 |
| Chipping hammers, 10-13 lb | 28-30 |
| 2-4 lb | 12 |
| Nut setters to 5/16 in., 8 lb | 20 |
| ½ to ¾ in., 18 lb | 30 |
| Paint spray | 2-20 |
| Plug drills | 40-50 |
| Riveters, 3/32- to 1/8-in. rivets | 12 |
| larger, weighing 18-22 lb | 35 |
| Rivet busters | 35-39 |
| Steel drills, rotary motors: | |
| To ¼ in., weighing 1¼-4 lb | 18-20 |
| ¼ to ⅜ in., weighing 6-8 lb | 20-40 |
| ½ to ¾ in., weighing 9-14 lb | 70 |
| ⅞ to 1 in., weighing 25 lb | 80 |
| Wood borers to 1-in. diameter, weighing 14 lb | 40 |

## II—Cost of Gas to Compress and Deliver Free Air

(Cents per 100 cu ft, based on fuel consumption of 10,000 Btu per bhphr)

| Bhp per 100 cfm free air | Price of gas in cents per 1000 cu ft of 1000-Btu gas | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 |
| 16 | 0.026 | 0.039 | 0.052 | 0.065 | 0.078 | 0.091 | 0.104 | 0.117 |
| 18 | 0.029 | 0.044 | 0.059 | 0.073 | 0.088 | 0.102 | 0.117 | 0.132 |
| 20 | 0.033 | 0.049 | 0.065 | 0.081 | 0.098 | 0.114 | 0.130 | 0.146 |
| 22 | 0.036 | 0.054 | 0.072 | 0.090 | 0.107 | 0.125 | 0.143 | 0.161 |
| 24 | 0.039 | 0.058 | 0.078 | 0.097 | 0.117 | 0.136 | 0.156 | 0.176 |
| 26 | 0.042 | 0.063 | 0.085 | 0.106 | 0.127 | 0.148 | 0.169 | 0.190 |
| 28 | 0.045 | 0.068 | 0.091 | 0.114 | 0.137 | 0.159 | 0.182 | 0.205 |
| 30 | 0.049 | 0.073 | 0.098 | 0.122 | 0.146 | 0.170 | 0.195 | 0.220 |

## III—Cost of Fuel Oil to Compress and Deliver Free Air

(Cents per 100 cu ft based on fuel consumption of about 0.45 lb per bhphr)

| Bhp per 100 cfm free air | Price of fuel oil (18,500 Btu per lb) in cents per gallon | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 16 | 0.050 | 0.067 | 0.083 | 0.100 | 0.117 | 0.133 | 0.150 | 0.167 |
| 18 | 0.056 | 0.075 | 0.094 | 0.113 | 0.131 | 0.150 | 0.169 | 0.189 |
| 20 | 0.063 | 0.083 | 0.104 | 0.125 | 0.146 | 0.167 | 0.188 | 0.210 |
| 22 | 0.069 | 0.092 | 0.115 | 0.138 | 0.160 | 0.183 | 0.206 | 0.230 |
| 24 | 0.075 | 0.100 | 0.125 | 0.150 | 0.175 | 0.200 | 0.225 | 0.251 |
| 26 | 0.081 | 0.109 | 0.136 | 0.163 | 0.190 | 0.217 | 0.244 | 0.272 |
| 28 | 0.088 | 0.117 | 0.146 | 0.175 | 0.204 | 0.233 | 0.262 | 0.293 |
| 30 | 0.094 | 0.125 | 0.156 | 0.188 | 0.219 | 0.250 | 0.281 | 0.314 |

## IV—Cost of Gasoline to Compress and Deliver Free Air

(Cents per 100 cu ft, based on fuel consumption of about 0.75 lb per bhphr)

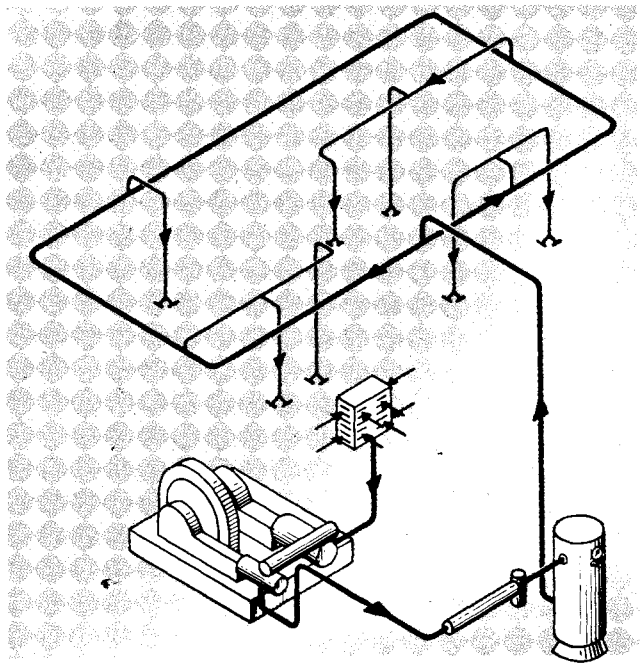
| Bhp per 100 cfm free air | Price of gasoline, cents per gallon | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 16 | 0.267 | 0.300 | 0.333 | 0.367 | 0.400 | 0.433 | 0.467 | 0.500 |
| 18 | 0.300 | 0.338 | 0.375 | 0.413 | 0.450 | 0.488 | 0.525 | 0.563 |
| 20 | 0.333 | 0.375 | 0.416 | 0.458 | 0.500 | 0.542 | 0.584 | 0.626 |
| 22 | 0.367 | 0.413 | 0.458 | 0.504 | 0.550 | 0.596 | 0.642 | 0.688 |
| 24 | 0.400 | 0.450 | 0.500 | 0.550 | 0.600 | 0.650 | 0.700 | 0.750 |
| 26 | 0.433 | 0.488 | 0.542 | 0.596 | 0.650 | 0.705 | 0.759 | 0.813 |
| 28 | 0.467 | 0.525 | 0.584 | 0.642 | 0.700 | 0.759 | 0.816 | 0.875 |
| 30 | 0.500 | 0.563 | 0.626 | 0.688 | 0.750 | 0.813 | 0.875 | 0.938 |

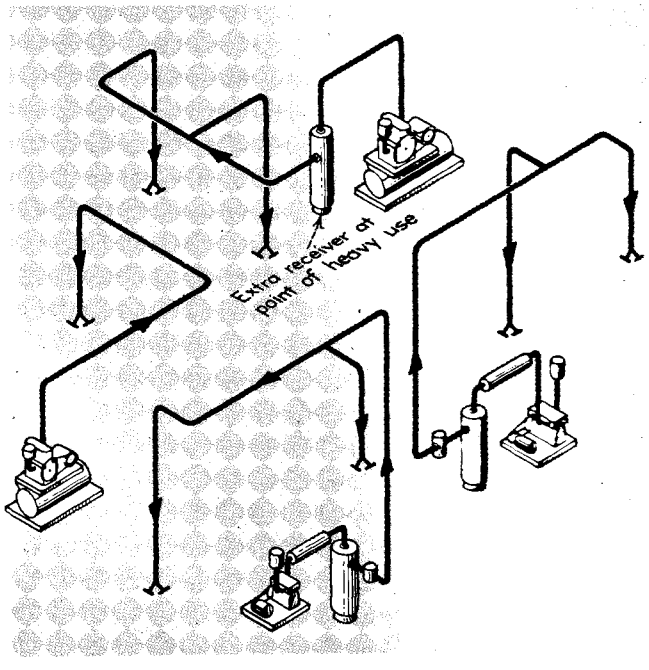
## V—Cost of Coal to Compress and Deliver Free Air

(Cents per 100 cu ft, based on coal at $1.00 per ton and an evaporation rate of 7 lb water per lb coal. Multiply figures in table by actual coal price in dollars per ton)

| Ihp per 100 cfm free air | Steam rate of engine in lb per indicated hphr | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 26 | 28 | 30 | 32 | 34 | 36 | 38 | 40 |
| 16 | 0.050 | 0.053 | 0.057 | 0.061 | 0.063 | 0.068 | 0.072 | 0.076 |
| 18 | 0.056 | 0.060 | 0.064 | 0.069 | 0.071 | 0.077 | 0.081 | 0.086 |
| 20 | 0.062 | 0.067 | 0.071 | 0.076 | 0.079 | 0.086 | 0.090 | 0.095 |
| 22 | 0.068 | 0.073 | 0.079 | 0.084 | 0.087 | 0.094 | 0.100 | 0.105 |
| 24 | 0.074 | 0.080 | 0.086 | 0.091 | 0.095 | 0.103 | 0.109 | 0.114 |
| 26 | 0.081 | 0.087 | 0.093 | 0.099 | 0.103 | 0.111 | 0.118 | 0.124 |
| 28 | 0.087 | 0.093 | 0.100 | 0.107 | 0.111 | 0.120 | 0.127 | 0.133 |
| 30 | 0.093 | 0.100 | 0.107 | 0.114 | 0.119 | 0.129 | 0.136 | 0.143 |

## Study plant air needs before choosing distribution system...






# System Layout

First step: Study your plant to see if it would be better served by one large compressor in a central location, or by several smaller ones in areas needing air. This important decision affects system costs from start to finish.

**Central system,** *above left,* has one or more large compressors in a more or less central location. Supply piping, often in the form of a loop, runs to areas needing air.

Advantages claimed for central systems include: low investment cost per unit of capacity, low unit power cost, chance to use synchronous motors to correct power factor, good pressure regulation, minimum wiring for motor drive.

**Unit system,** *above right,* has compressors spotted in areas using air. In the usual plant, each compressor serves the area in which it is located, with only emergency connections between the different areas.

Advantages cited for unit systems include: low initial investment, less pressure loss in piping, reduced engineering and planning, simpler installation, greater flexibility, easier financing of plant expansion, simplified purchasing. All these are fully discussed in POWER, Jan 1953, pp 75-77.

**Study Needed.** There are no simple rules to use in choosing a system. Each plant must be analyzed separately and the decision based on the results. For many years central systems have been popular in large industrial plants, and have given excellent service. Unit systems, while used in both large and small plants, are newer and are not yet as extensively applied in large plants.

## Compressed-Air Piping

Regardless of compressor or distribution system chosen, piping is of major importance in every setup. Because piping conveys air from high-pressure source (compressor) to point of use (tool), it can be a definite help or hindrance in plant operation.

Good piping design limits pressure drop between compressor and tool because low pressure at the tool cuts production. We haven't space for a complete rundown on all angles of piping design but here are some helpful pointers:

**Intake, Discharge.** Have intake pipe at least as large as compressor intake opening. For every 10 ft of run from compressor, make line diameter one inch greater. Keep air velocity in intake below 2500 fpm. This cuts friction loss.

Make discharge line at least as large as compressor outlet opening; use as few bends as possible. Be sure run is short and direct. Fit valved drain to lowest point of discharge line and in any pockets formed by piping.

Support intake and discharge piping so vibration and strain don't reach compressor cylinder, aftercooler or receiver. Use gate-type shutoff valves in air lines to keep friction loss low.

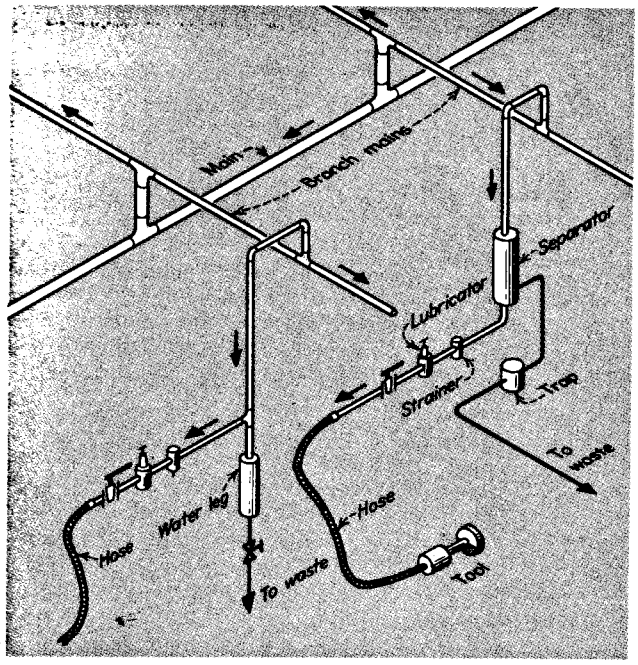
**Distribution Piping.** Line from receiver to point of use is generally sized so pressure loss is reasonable – below 5 psi. Provide outlets on each header or main for connection of hoses to air-operated tools or devices. Fit outlet to top of pipe so moisture won't drain from main into hose. If several tools connect to one outlet, be sure it is big enough to prevent excessive pressure loss. Sketch, *above,* shows a typical main with connections for several tools.

Always remember: *Low air pressure at tools can cause a far greater loss in plant income than a few points in compressor efficiency.* Next to low pressure, moisture and solids are the worst enemies of good air-tool operation. Make full use of separators, strainers, traps, drop legs.

**Intake location** is of prime importance because high temperatures reduce compressor output, as Table I shows. See that intake is as far as possible from heat, dirt and moisture sources and not too close to building walls and windows. Put intake on north side of building, if possible.

**Receivers** that are sized liberally reduce compressor loaded periods and insure more thorough cooling of air before it reaches tools. Use ASME standard receivers and fittings

# . . . then pipe air tools properly




except where local codes differ. It is a good plan to install extra receivers near points of heavy usage to insure adequate volume and pressure, and smooth out flow in supply mains and branches.

**Safety devices** are needed to protect personnel and equipment from excessive pressure and other conditions that lead to trouble. Table III lists typical devices used in large plants; many would not be justified in small installations. Even the simplest system, however, is always fitted with a pressure-relief device of some sort on the discharge side.

## Compressor Cooling

Good cooling is essential to good operation. Though air-cooled compressors may run satisfactorily in warm areas, make every effort to put them in cool spots. Capacity will be greater and there'll be fewer operating problems.

**Suitable strainers** in main water-supply line to water-cooled compressors protect against solids. Run piping so it won't interfere with maintenance work on cylinders and drive. Put drain valves at all low points so entire system may be drained during shutdown in freezing weather.

Fit each cylinder and intercooler with its own regulating valve, even though an automatic valve starts and stops water flow to compressor. Put such valves on inlet side, with outlet free to flow into an open funnel or sight glass.

**Cooling water** should enter cylinder or intercooler at bottom, leave from top. This keeps jackets full and helps eject any air. A check valve between cylinder and intercooler above it keeps water from draining back into cylinder when unit is shut down.

Extremely cold water may cause condensation on cylinder walls. This destroys lubricant, increases wear. To avoid this, pass cooling water through intercooler first, then to low- and high-pressure cylinders in turn.

Table II shows recommended water quantities. With them, temperature of air leaving intercooler or aftercooler will be within 20 and 15 F, respectively, of the temperature of water entering the cooler (for ordinary plant loads).

Use enough plugged fittings in water lines to cylinders and coolers to permit cleaning jackets and tubes with an air hose or with a caustic-soda solution.

### I — Effect of Initial or Intake Temperature on Delivery of Air Compressors

*(Based on a nominal intake temperature of 60F)*

| Initial temperature, F | Initial temperature, F, abs | Relative delivery | Initial temperature, F | Initial temperature, F, abs | Relative delivery |
|---|---|---|---|---|---|
| − 20 | 440 | 1.18 | 70 | 530 | .980 |
| − 10 | 450 | 1.155 | 80 | 540 | .961 |
| 0 | 460 | 1.13 | 90 | 550 | .944 |
| 10 | 470 | 1.104 | 100 | 560 | .928 |
| 20 | 480 | 1.083 | 110 | 570 | .912 |
| 30 | 490 | 1.061 | 120 | 580 | .896 |
| 32 | 492 | 1.058 | 130 | 590 | .880 |
| 40 | 500 | 1.040 | 140 | 600 | .866 |
| 50 | 510 | 1.020 | 150 | 610 | .852 |
| 60 | 520 | 1.00 | 160 | 620 | .838 |

### II — Cooling Water Recommended for Intercoolers, Cylinder Jackets, Aftercoolers

*Gpm per 100 cfm actual free air*

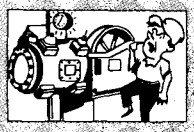
| | |
|---|---|
| Intercooler separate | 2.5 to 2.8 |
| Intercooler and jackets in series | 2.5 to 2.8 |
| Aftercoolers: | |
| 80-100 psi, 2-stage | 1.25 |
| 80-100 psi, single-stage | 1.8 |
| Two-stage jackets alone (both) | 0.8 |
| Single-stage jackets: | |
| 40 psi | 0.6 |
| 60 psi | 0.8 |
| 80 psi | 1.1 |
| 100 psi | 1.3 |

### III — Typical Compressor Safety Devices

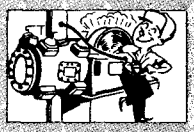
| Name | Function |
|---|---|
| Relief valves | On compressor discharge side to relieve excessive pressure. Don't use any shut-off valves between compressor and the safety valve |
| Overspeed shutdown | Trips out drive when compressor exceeds predetermined safe speed |
| Oil-failure shutdown | For large compressors fitted with pressure lubrication, this device protects bearings by stopping unit when oil pressure fails for any reason |
| Jacket-water valve | Shuts down compressor if water pressure fails. It is operated by either pressure or temperature |
| Over-pressure shutdown | Stops compressor when discharge pressure goes above pre-set safe value |
| Excessive-temperature shutdown | For isolated compressors this gives protection against high discharge temperature by automatically stopping unit |
| Main-bearing protection | Thermal shutdown devices stop compressor if bearing temperature goes too high |
| Multistage temperature protection | Recording thermometers for each stage are good for this, give continuous reading of each stage's outlet temperature |

# TROUBLE-SHOOTING GUIDE

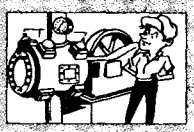
## Water-Cooled Compressors



**DISCHARGE PRESSURE LOW — demand greater than compressor's capacity; rings worn; leaky packing; wrong speed; excessive leakage in system**

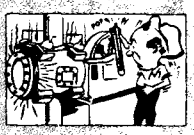


**NOT ENOUGH CAPACITY — too much leakage in piping or valves; discharge pressure too high; wrong speed; clogged filter; worn piston and rings**

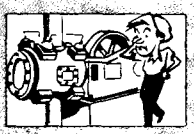


**COMPRESSOR DOESN'T DELIVER AIR — dirty intake filter; suction line clogged; improperly installed valves; strips missing from compressor valves**

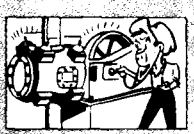
**EXCESSIVE COMPRESSOR VIBRATION — unit not properly secured to foundation; wrong type of foundation; piping not correctly supported**



**COMPRESSOR OVERHEATS — broken valve strips; not enough cooling water; air-intake filter clogged; discharge pressure too high; internal leakage**

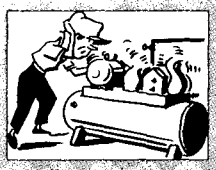


**COMPRESSOR OVERLOADS MOTOR — belts in drive too tight; discharge pressure or speed too high; discharge line clogged; wrong motor hookup**

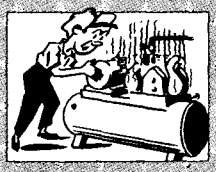


**COMPRESSOR KNOCKS — loose flywheel or pulley; too much clearance in wrist-pin bushing, crankpin or main bearings; loose valve or piston nut**

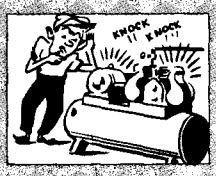
## Air-Cooled Compressors



**NOT ENOUGH CAPACITY — excessive leakage in pipes, fittings or valves; discharge pressure too high; wrong speed; clogged intake filter; worn piston and rings; leaky cylinder-head gasket; belt slips; intercooler leaks**



**COMPRESSOR OVERHEATS — valve strips broken; direction of rotation wrong; intake filter clogged; discharge pressure too high; internal leakage; not enough lubricating oil**




**COMPRESSOR KNOCKS — loose flywheel or pulley; loose valve in cylinder or loose unloader; excessive end play in motor rotor; too much wrist-pin- or crankpin-bearing clearance; belt not aligned; unlevel mounting**

**EXCESSIVE COMPRESSOR VIBRATION — unit not properly secured to foundation; wrong foundation; shipping blocks not removed from under base; motor rotor out of balance; one cylinder in a 2-cylinder unit not working**

**UNIT BLOWS FUSES — fuses too small; low voltage; pressure-switch differential too small; unit starting against a full load; motor defective; compressor or motor binding**

# *Operation & Maintenance*

Your best guide to compressor operation and maintenance is the manufacturer's book. Too many operators file instruction books when they arrive and then promptly forget them. This is just too bad, because compressor builders put much time, energy and money into producing usable books that will answer most of your questions.

Start by following carefully the installation instructions for your compressor and its auxiliaries. A job that's installed right saves you many future headaches and insures topnotch performance.

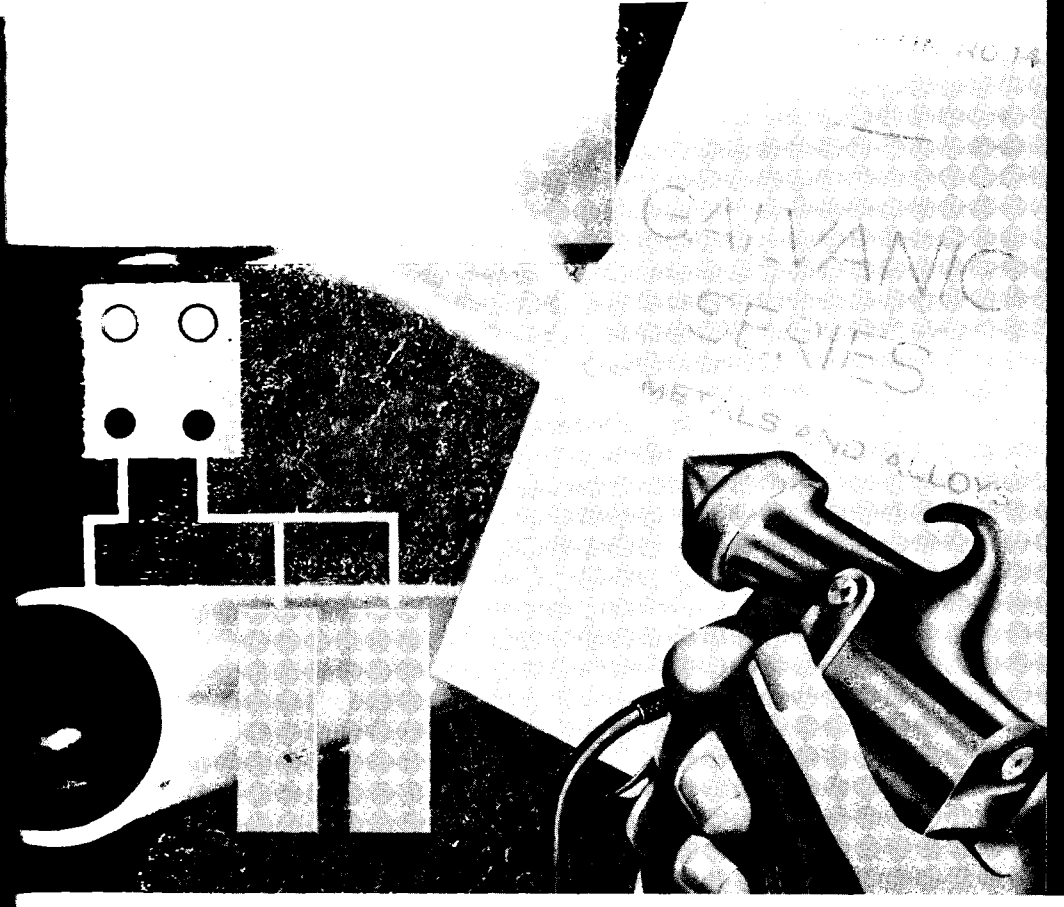
Once a compressor is on the line and working right, regular inspection, lubrication and overhaul are chores that pay big dividends if done well. Here again, your best guide is the instruction book. It deals with your compressor exclusively, and is based on long experience.

Lastly, remember that many steps taken during system planning have direct effects on operation and maintenance. So plan your system well, working with a consulting engineer and the manufacturer whose compressor you intend to use.

If you live by these simple rules, troubles will be rare. If they do pop up, use the trouble-shooting hints above to give you a lead. Then turn to your instruction book for detailed information on cures.


## ACKNOWLEDGMENTS

For illustrations and technical data in this handbook, POWER is indebted to the following manufacturers: R P Adams Co, Inc; Aftercooler Engrg Co; Air-Flo Compressor Co; Air Maze Corp; Allis-Chalmers Mfg Co; V D Anderson Co; American Air Filter Co, Inc; American Blower Corp; Armstrong Machine Works; J B Beaird Co, Inc; Beach-Russ Co; Binks Mfg Co; Brown Boveri Corp; Brunner Mfg Co; Buckeye Air Compressor Co; Bury Compressor Co; Carrier Corp; Champion Pneumatic Machinery Co; Chicago Pneumatic Tool Co; Clark Bros Co; Clark Mfg Co; Cooper-Bessemer Corp; The Cornelius Co; Curtis Mfg Co; Davey Compressor Co; DeLaval Steam Turbine Co; DeVilbiss Co; Dollinger Corp; Eclipse Fuel Engrg Co; Elliott Co; H Emerson Thomas & Assoc; Fuller Co; Gardner-Denver Co; Gast Mfg Co; Gray Co, Inc; Hankison Corp; Ingersoll-Rand Co; Jaeger Machine Co; Joy Mfg Co; Kaye & MacDonald Inc; Kellogg Div, American Brake Shoe Co; Lamson Corp; Le Roi Co; Nash Engrg Co; Niagara Blower Co; W H Nicholson & Co; Nordberg Mfg Co; Norwalk Co; OK Clutch & Machinery Co; Pennsylvania Pump & Compressor Co; Quincy Compressor Co; Roots-Connersville Blower Corp; Sarco Co, Inc; Schramm, Inc; Spencer Turbine Co; C E Squires Co, Inc; Standard Stoker Co; Strong, Carlisle & Hammond Co; Swartwout Co; Trane Co; Union Steam Pump Co; U. S. Hoffman Machinery Corp; Voss Machine Wks; Wayne Pump Co; Westinghouse Electric Corp, Sturtevant Div; Wilkerson Corp; Worthington Corp; Wright-Austin Co; Yeomans Bros Co; York Corp.



Why metals corrode

Corrosion types

Tools for the job

Combatting corrosion

Corrosion testing

Anti-corrosion programs

# CORROSION

Look at your plant through the eyes of a corrosion engineer and — if you don't now have a corrosion-control program — chances are you'd come up with enough corrosion-cost-cutting ideas to pay for your efforts many times over.

In coming to grips with the problem you'd tap know-how from many quarters — metallurgy, chemistry, electrical engineering, even geology and meteorology (in studying soils and weather effects on corrosion). Some of the weapons you'd use have been around for years. But you'd probably consider many of these newer ones too:

Latest corrosion-resistant metals, although they generally cost more to begin with, soon pay for themselves by standing up against corrosive waters, high temperatures, chemical attack.

Inert barriers, many of them today's newest synthetics — silicones, epoxies, vinyls — bring corrosion to a dead stop by setting up an impregnable wall around less corrosion-resistant materials.

Recent developments in the water-treatment field — more efficient deaeration, new inhibitors — promise more effective corrosion control in water systems.

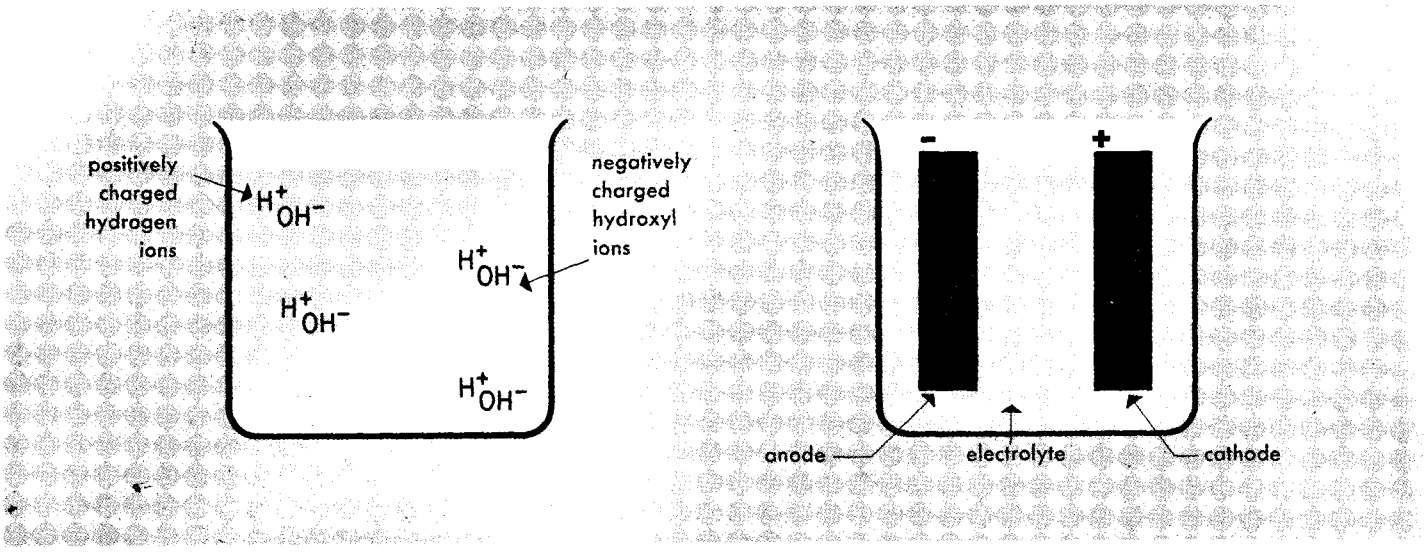
And cathodic protection—though its principles date back to experiments by Sir Humphry Davy in 1824 — has achieved wide usefulness only within recent years.

Why so much emphasis on corrosion now? At least part of the answer lies in the economics. Material and manpower costs continue to climb. Industry's annual bill for corrosion — at last count, pegged at roughly six billion dollars — follows the trend closely. Result: Corrosion-control programs offer an area fertile in cost-cutting opportunities.

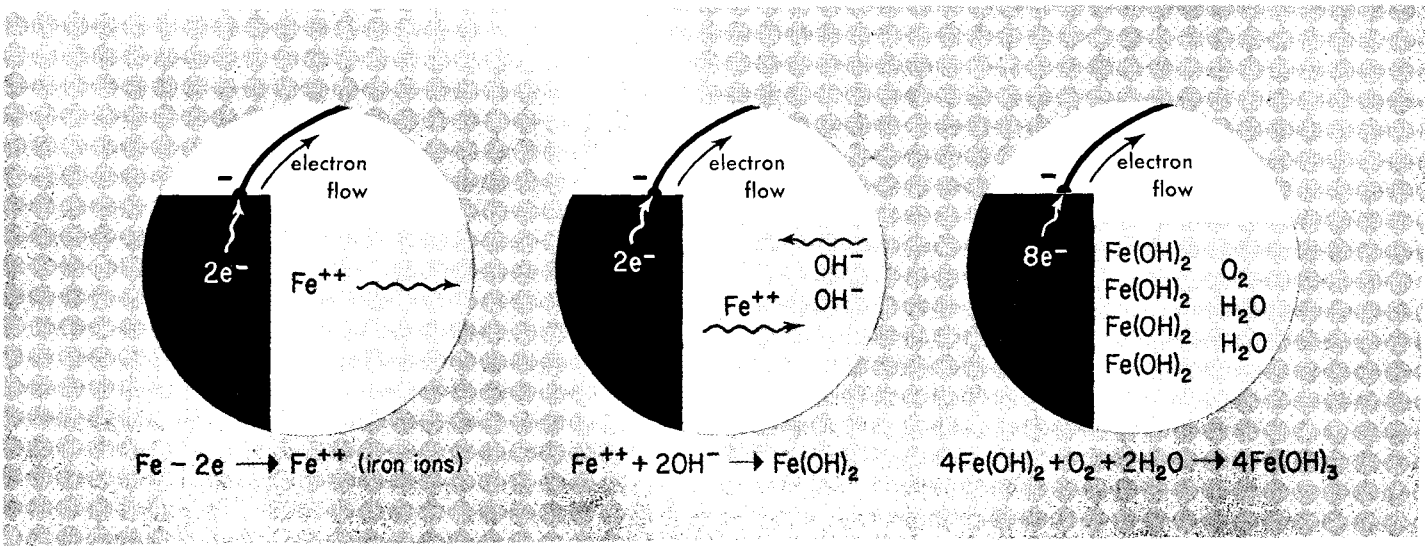
Engineering-wise, today's higher temperatures, pressures and tougher corrosive environments in general, make more exacting corrosion control a must.

Thus, we view corrosion as both an engineering and economic problem in this report. It leads off with basics, follows up with anti-corrosion weapons, practical applications, corrosion testing and programs. Let it guide you in bringing the latest thinking to bear on the corrosion problems of your plant.

# Corrosion – nature's wasteful way




**The electrolyte couples anode and cathode areas to form**




**Oxidation (corrosion) reactions take place at the anode,**

Corrosion is simply nature's way of trying to revert refined metals to their natural state. Take iron for example. When iron corrodes it forms rust. Analyze rust and you'll find it's iron oxide. Iron ore, too, is iron oxide. Thus, we can picture corrosion as an attempt to undo man's "meddling" with the metallic ores found in nature.

**Corrosion** basically is an electrochemical action, much like that in an electric dry cell. Electricity flows between metal areas through a solution. Deterioration (corrosion) takes place where the current leaves the metal and enters the solution. This area is called the *anode*.

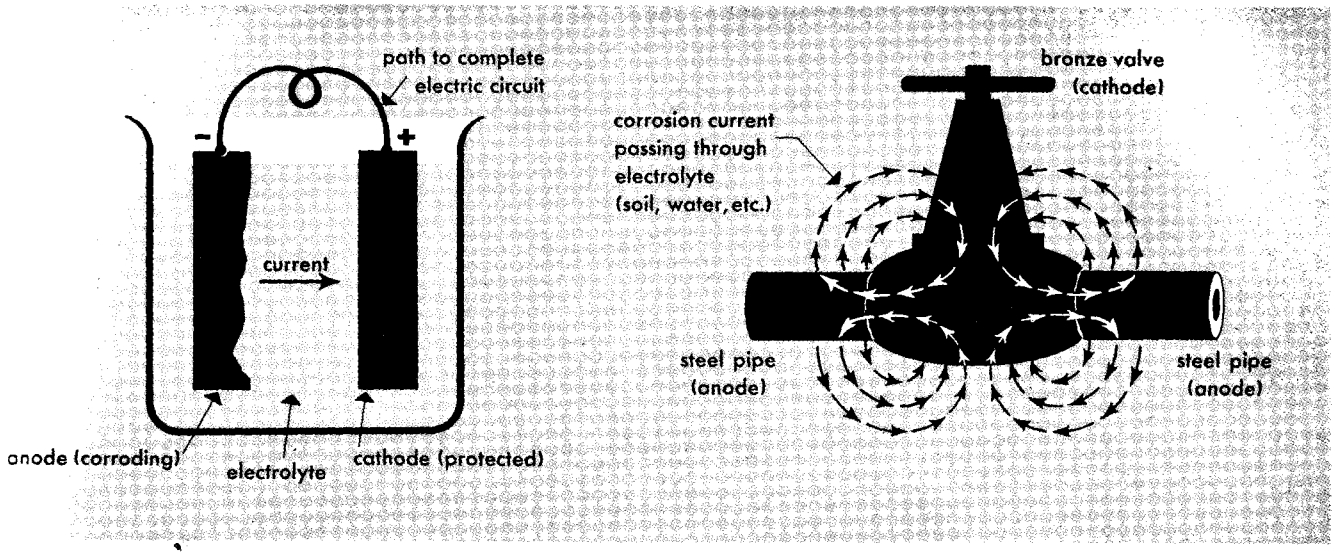
**Electrolyte**—the conducting solution—may be water, soil, chemical solutions, etc., depending on the application.

**Cathode** is the area at which current returns to the metal. The electrodes (anode and cathode) may be two different metals or different areas of the same metal. In both cases we find a difference of potential (voltage) between the two electrodes, causing current to flow between them, just as a dry cell causes flow in the common electric circuit.

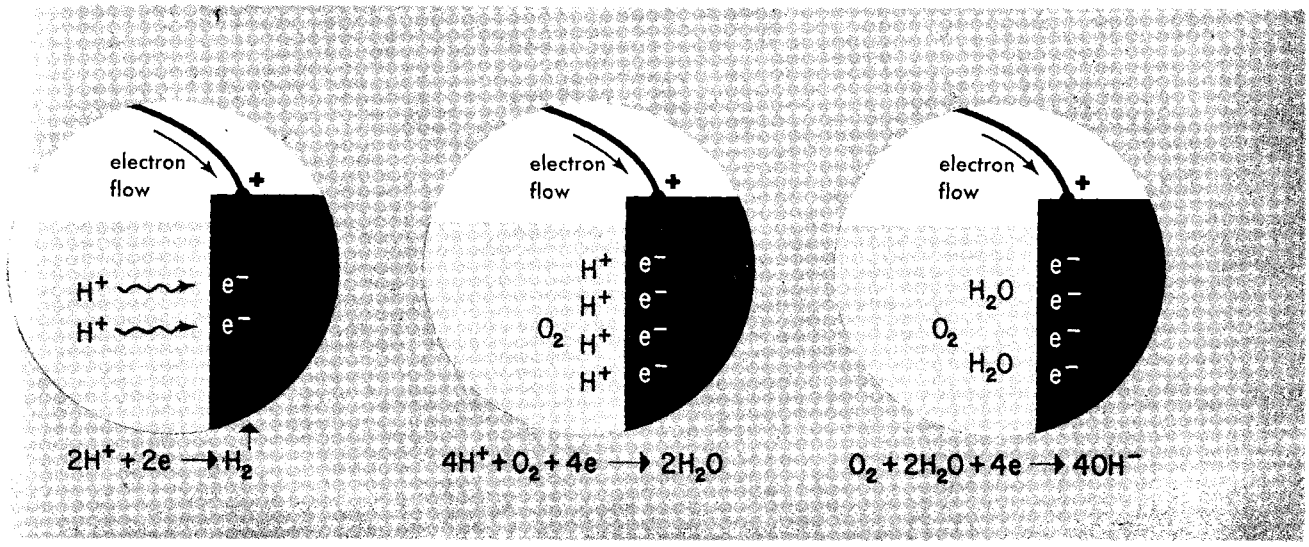
**Electron path.** Besides the electrodes and electrolyte we also need a path to complete the electric circuit. In actual corrosion, the metal structure itself may provide the path. Or the circuit may be completed by physical contact between the metals.

**Electron flow** results from a difference in potential between two points in a circuit. When corrosion occurs, electrons (negative charges, $e^-$) leave the anode and flow to the cathode along the path between the two. The electrons are released by metal atoms at the anode surface. When an electron leaves an atom, the atom becomes positively charged because it has a deficiency of negatively charged electrons. The atom is then a positively charged *ion*.

# of returning metals to their ores




**a galvanic cell.** **It may look like this in your plant**




**while reduction (protective) reactions go on at the cathode**

The electrolyte also contains ions. Pure water, for instance, contains equal numbers of positively charged hydrogen ions ($H^+$) and negatively charged hydroxyl ions ($OH^-$). These ions play an important role in corrosion. Let's see how.

**During corrosion of iron** in water, each iron atom releases two electrons as it becomes ionized. The electrons flow in the circuit path to the cathode. Iron ions form at the anode, are attracted by negatively charged hydroxyl ions in the electrolyte and pass into solution. Electrons arriving at the cathode neutralize some of the hydrogen ions that have collected there. As the process continues, hydroxyl ions left behind attract more iron ions into solution, forming the unstable compound ferrous hydroxide, $Fe(OH)_2$.

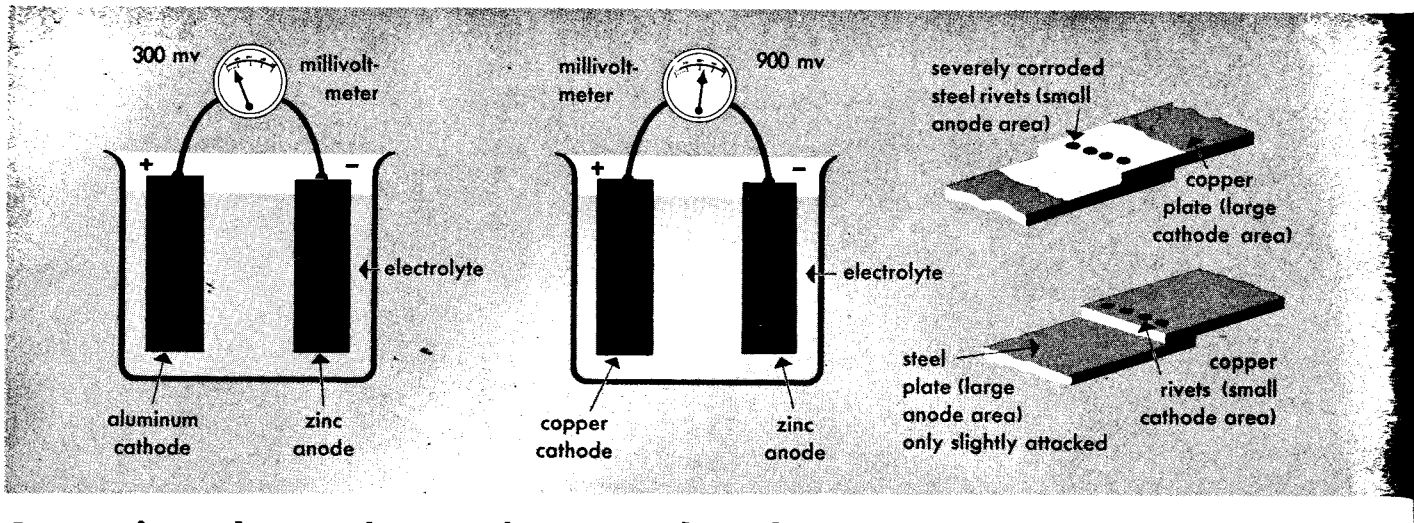
**Final step in corrosion** of iron is the oxidation of unstable ferrous hydroxide. It combines with oxygen in the electrolyte to form ferric hydroxide, $Fe(OH)_3$—common rust.

Remember: Anode and cathode processes can't occur separately. One supports the other. But corrosion itself takes place at the anodic areas.

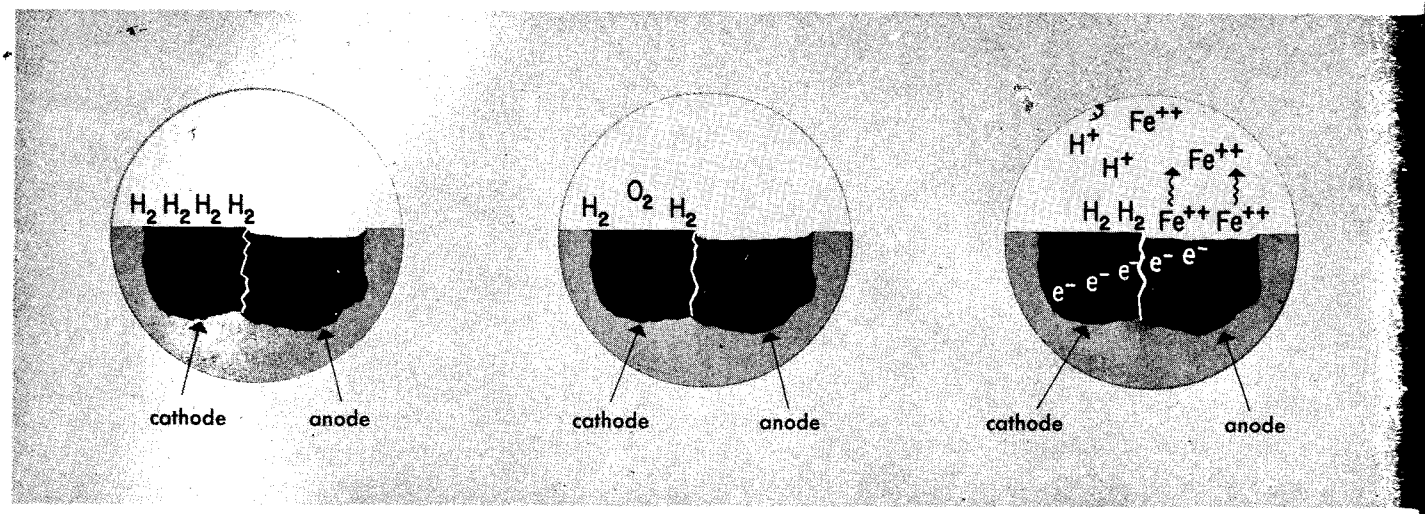
**Rust** may break away from the metal surface or remain there to influence the progress of corrosion. Alkalinity, oxygen content and agitation of the electrolyte all come into

### A word about sign conventions

Positive and negative sign conventions used here are opposite those electrical engineers use because the U.S. Bureau of Standards calls platinum (the cathode) positive to magnesium (the anode). To avoid confusion remember: Cathode is the protected member; anode corrodes.




## Corrosion depends on the metals, electrolyte, relative areas




## $H_2$ polarizes the cathode, $O_2$ depolarizes it. Local cells

play in determining where and how rust will form on a metal.

We've already seen that potential differences between different metals, or from point to point on a single metal, are a necessary condition of corrosion. The action between different metals is called galvanic because they form a galvanic couple (two metals). Corrosion currents flowing between two points on the same metal surface are *local.* But whether the current is due to local or galvanic action, we'll need to understand how it originates before we can bring the right preventive measures into play.

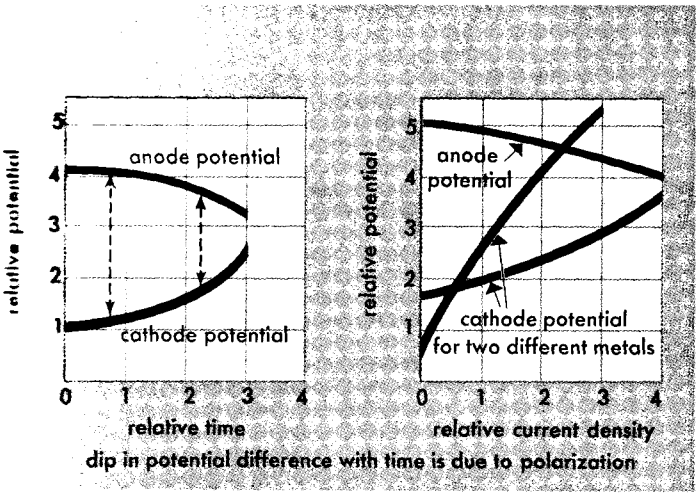
**In dealing with galvanic corrosion** it's essential to know which metal in the couple will corrode (act as the anode). The galvanic series of metals and alloys, *facing page,* can supply a quick answer. Metals near the top of this series are anodic with respect to metals below them. And metals grouped close together have less tendency to produce a galvanic couple than metals from widely separated groups. Thus, zinc shows strong anodic characteristics when coupled with copper. Tin and lead, on the other hand, have little galvanic effect on each other.

In using any galvanic series you'll need to exercise caution. These series may vary somewhat, depending on the corrosive environment (electrolyte). And the potential between two metals that are close to each other in the series, may reverse under different conditions.

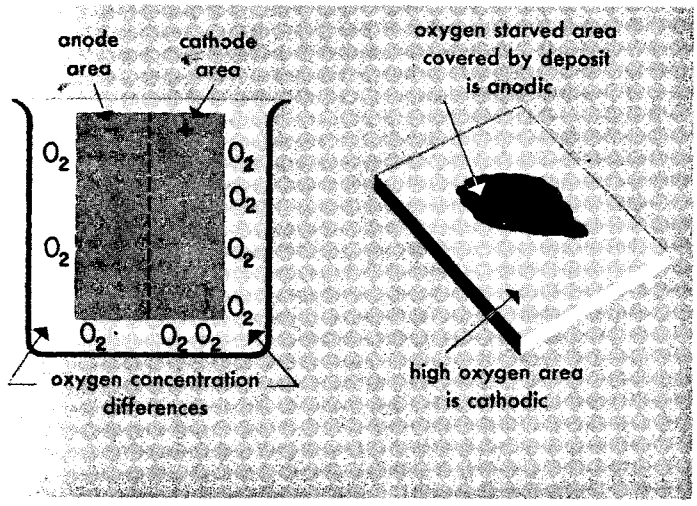
**Stainless steels** are listed twice, as active and as passive. Under certain conditions, they'll act cathodically even with respect to copper. But put them in a different environment and they're only slightly more passive than ordinary iron and steel. We'll have more to say about this later under inhibitors and passivation.

**Corrosion rate.** How fast do anode metals corrode? What controls corrosion rate? Right answers to these questions often spell the difference between good and poor corrosion control. Again, we find at least part of the answer by looking at the galvanic series. Coupling widely separated metals in the series yields relatively greater galvanic potentials. Driving force behind galvanic corrosion is roughly proportional to these potentials. Differences as little as 0.1 volt indicate substantial galvanic action. Thus, we usually make measurements with a sensitive millivoltmeter.

**Polarization.** As corrosion products build up at anode and cathode, the voltage differences tend to dip. Anode and cathode voltages drift toward each other, slowing down corrosion rate. This voltage change is called *polarization.* Polarizing at the cathode is usually greater than at the




## as well as polarization


anode area
cathode area
oxygen concentration differences
oxygen starved area covered by deposit is anodic
high oxygen area is cathodic

## are set up by metal-ion and $O_2$ concentration differences

### Galvanic Series

**Anodic, corroded end**

Magnesium
Magnesium alloys
Zinc
Aluminum
Cadmium
Mild steels
Alloy steels
Wrought iron
Cast iron
Stainless steels (active)
Ni-Resist
Soft solders
Lead
Tin
Muntz metal
Brasses
Copper
Bronzes
Copper-Nickel alloys
Nickel
Inconel
Stainless steels (passive)
Hastelloy C
Titanium
Silver
Graphite
Gold
Platinum

**Cathodic, protected end**

Metals near the top of this series act as anodes, suffer corrosion when coupled with one nearer the bottom. Galvanic couples of metals close together in this series usually corrode more slowly than couples composed of metals from the extremes.

Note too that certain metals are grouped together. Couples of metals within these groups have the least tendency to corrode.

anode. So we're more likely to be concerned with its cathodic effects. Hydrogen gas, for instance, can blanket the cathode surface, cutting corrosion at the anode. But hydrogen may soon be removed by combining with oxygen to form water.

Some metals polarize easier than others. So it's important to know the metal's polarizing tendency as well as its initial potential.

**Relative size of anode and cathode** also affect polarization. Here's why: Drifting potential at the cathode depends not only on current but on *current density*. For the same current flow, current density is greater on a small electrode than on a big one. Also, as hydrogen ions reach a large cathode they are spread relatively thin. Thus they can combine more readily with oxygen, retarding polarization. In brief, relatively small cathodes promote high current density, retard the action of oxygen as a cathodic depolarizer. We're flirting with corrosion when we couple large cathodes with small anodes.

**Local corrosion.** Potential differences between areas on the same metal cause local corrosion currents. They often result from variations in the conditions of the air, soil, water, etc., next to different sections of the metal. For example, we find different metal-ion concentrations where relative speeds of electrolyte over the metal are greater at one point than another. Metal ions accumulate where speeds are lower, become cathode areas. Anodes form where relative movement is high, causing these areas to corrode.

If we rotate a metal disk at high speed in water, we find that it tends to corrode near the edge where linear velocities are highest. Speed sweeps away metal ions, forming anode areas. But by choosing an alloy to suit velocity conditions, the effect of low metal-ion concentration can be avoided.

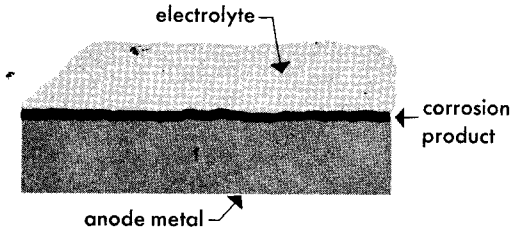
**Oxygen concentration cells** can also cause local corrosion. Surprisingly enough, high-oxygen-concentration areas form cathodes. And we can measure the corrosion current flow between points of differing oxygen density.

Common condition causing oxygen-cell attack is the presence of a deposit at one area of an otherwise freely exposed metal. A small sand hill on a clean brass surface attacks brass under the sand. Electrons flow through the metal to the surface outside the sand. Result is the *reduction* of oxygen in the exposed area (the cathode).

Note that in all corrosion cells, whether they're local or galvanic, reduction reactions take place at the cathode (protected area); oxidation reactions at the anode (corroding area). One chemical reaction supports the other.

# Here's how you can spot the many common varieties of corrosion

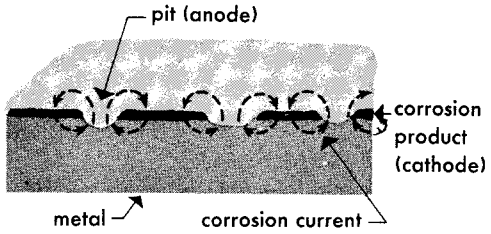
**It can show up in a host of ways and forms. And many of the most common types of corrosion conditions overlap each other**




## Uniform attack

Look for a general wasting away of the surface. You'll find this condition all too common where metals are in contact with acids, other solutions. But the presence of a solution isn't always essential. High-temperature oxidation, for instance, is a form of uniform attack that can take place in a relatively dry atmosphere.

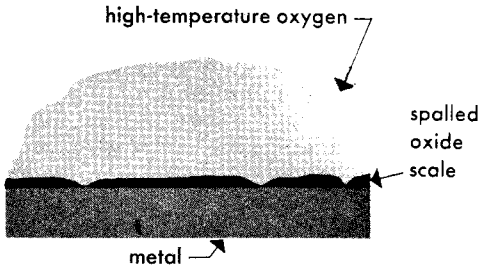
The corrosion product may form a protective layer on the metal, slowing down corrosion. Or, as in the case of direct chemical attack, the corroded material easily dissolves in the corrosive material.




## Pitting corrosion

When protective films or layers of corrosion product break down we get localized corrosion—pitting. An anode forms where the film breaks, while the unbroken film or corrosion product acts as the cathode. Thus we've, in effect, set up a closed electrical circuit.

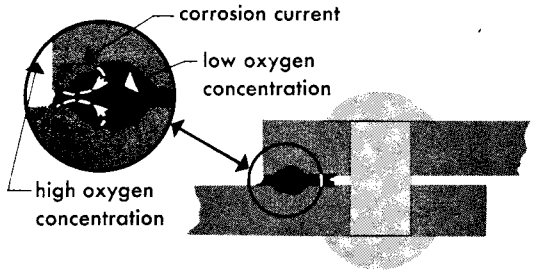
Corrosion pits take a heavy toll in machinery and equipment because they concentrate their attack over a small area. Pits also act as starting points for stress concentrations that spell trouble, especially where pits line up in rows that can become major breaks.




## High-temperature corrosion

To predict the effect of high-temperature oxidation we need data on: (1) metal composition (2) atmosphere composition (3) temperature, and (4) exposure time. So it's not easy to tell what will happen in one case, from the results of another. But we do know that most light metals (those lighter than their oxides) form a nonprotective oxide layer that gets thicker as time goes on. The layer forms, spalls and reforms.

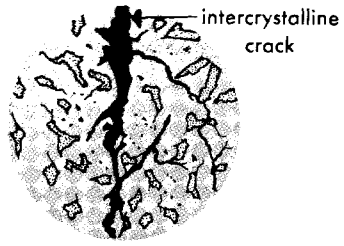
Other forms of high-temperature corrosion include sulfidation, carburization and decarburization.




## Concentration cells

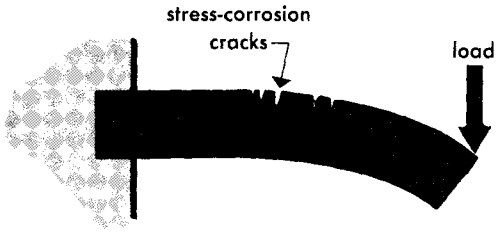
You'll recognize this condition by its presence in crevices. It sets up differences in solution concentration. The crevice, above, for example, hinders diffusion of oxygen. Result: High and low oxygen areas that cause concentration cells. Low oxygen area is anodic.

Metal-ion concentration cells, much like their oxygen counterparts, also strive to balance out concentration differences. Thus, when the solution over a metal contains more metal ions at one point than another, metal goes into solution where ion cencentration is low.



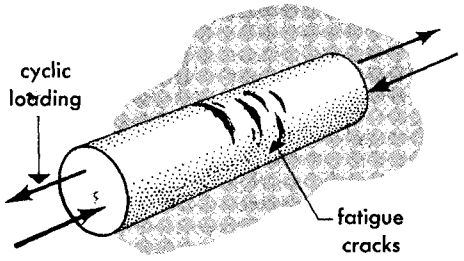

## Intergranular corrosion

You may be faced with intergranular corrosion for a variety of reasons. But the result is almost always the same – selective attack along the metal's grain boundaries—intercrystalline cracking, such as we picture in the photomicrograph above. In some austenitic stainless steels, chromium carbides may precipitate at grain boundaries when cooling from welding temperatures. Corrosion is free to attack chrome-starved areas.




## Stress corrosion cracking

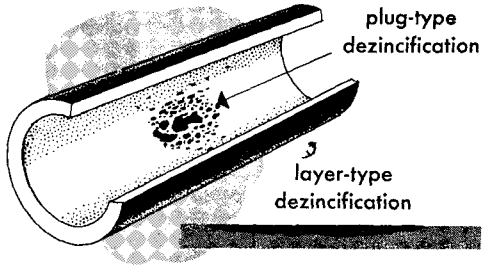
Team up high tensile stresses with a corrosive atmosphere and you're likely to be in for trouble. Here's how it develops. Tensile stresses build up at metal surface under static loading. Corrosive action concentrates stresses, causes them to exceed metal's yield point. Result shows up as a local failure. Under continued exposure, metal alternately corrodes, builds up high stress concentrations. Eventually the part may fail.




## Corrosion fatigue

In much the same way that static stresses link up with corrosion to produce stress-corrosion cracking, cyclic loads work hand-in-hand with corrosion to cause corrosion fatigue. Metal failure takes place substantially below the fatigue limit for non-corrosive conditions.

Surprisingly enough, the combined deteriorating effect of these two bed brothers – corrosion and fatigue – is greater than the sum of their individual damages. So it pays to apply best possible corrosion protection when dealing with metals under alternating stresses.

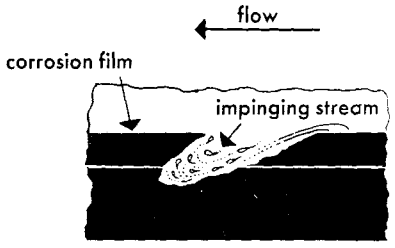



## Selective attack

Basically, one element of a metal or alloy is singled out for corrosive attack. Common types are dezincification and graphitic corrosion.

When we expose copper-zinc alloys (brasses) containing less than 85% copper to wet conditions for prolonged periods, zinc may be lost from brass. Resulting porous zinc-free mass of copper has little mechanical strength.

Common cast iron can act this way too. In some corrosives, iron corrodes out, leaving nothing more than a porous graphite residue that virtually crumbles.

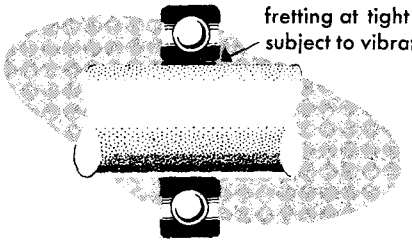



## Impingement attack

Similar in their method of attack and net effects are impingement corrosion and cavitation corrosion. Here's how they do their damage:

An impinging water stream breaks through corrosion scale, dissolving the metal. Effect depends mainly on liquid speed.

Cavitation, a common form of corrosion in pumps, depends on the hammer-like effect produced by collapsing air bubbles. Bubbles break down when they pass from a low-pressure to a high-pressure area.




## Fretting corrosion

Picture the ball bearing above supporting a heavily loaded high-speed shaft. Its inner race is press fit on the shaft. If high-frequency vibrations produce even minute slippage between these surfaces, local attack may start fatigue cracks, especially where stresses concentrate. Take shaft and bearing apart. You'll find their mating areas pitted.

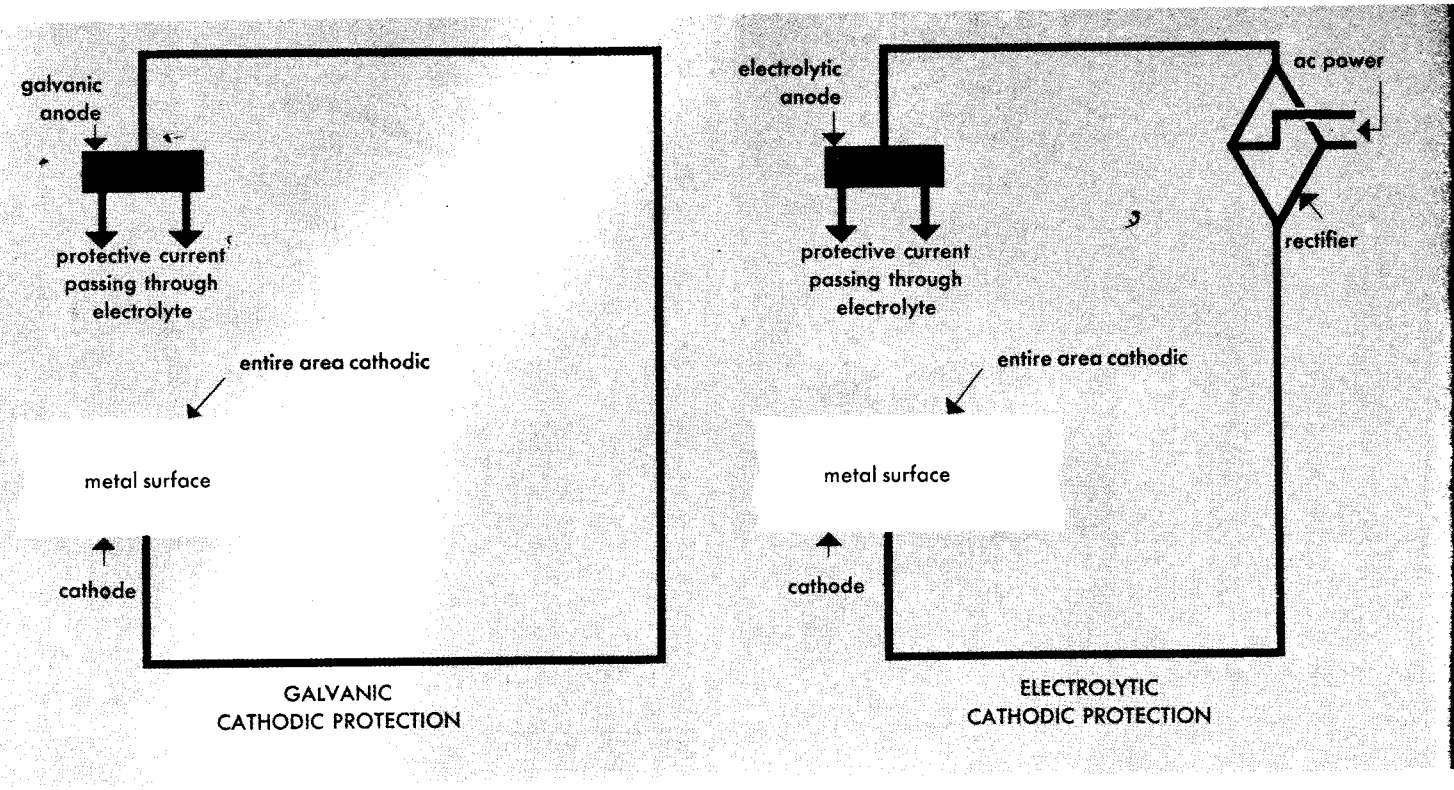
Likely explanation for fretting: Slippage shears away surface-protective films, laying bare the undersurface to galvanic attack and concentration-cell corrosion.

# Your weapons in the endless war on corrosion

So far we've talked almost exclusively about fundamentals — electrochemical theory, basic corrosion types, etc. In the next 14 pages we turn to the more practical elements of the problem — weapons for the fight against corrosion.

**Weapons we'll consider** include cathodic protection, engineering metals (ferrous and nonferrous), inert barriers (organic, metallic, vitreous), ways of altering the corrosive environment, inhibitors and temporary protection.

Not all these techniques will apply in your plant. Perhaps your corrosion problem can only be handled by changing the corrosive environment. But in any case, it'll pay you to know *all* the tools available. Remember: Your future machinery and equipment may not fit your present corrosion-control methods.




## CATHODIC PROTECTION . . . electrolytic and

The great value of cathodic protection lies in its simplicity and direct effectiveness. To see how it works we'll make use of a modification of the galvanic cells we've viewed thus far: The cathodic protection battery. It's nothing more than our original galvanic cell with an auxiliary anode acting as a substitute for the anode on the metal surface we want to protect.

**Auxiliary anodes** may be either electrolytic (energized by an external source of direct current) or galvanic (made up of a metal higher in the galvanic series than the metal to be protected). In either case, the electrical energy supplied by the auxiliary anodes forms a *fence* that prevents current flow in the local cells on the protected surface. With current flow stopped, metallic ions can't escape from the area we want to protect.

**In our original galvanic cell,** anodes on the metal surface released metallic ions, causing the metal to corrode. The cathodic protection battery transfers the corrosion process to the auxiliary anodes. These anodes are eventually consumed in protecting our metal structures. But anodes can be replaced. In brief, the method is fighting corrosion with corrosion — protecting one metal at the expense of another.

**Most common applications** of cathodic protection are for submerged (in soils, liquids) metal surfaces but the same principles apply to the protection of metal in any electrolyte.

**Current density.** A must in planning any cathodic protection system is finding the current density needed to maintain the electrical *fence* at all areas to be protected. Right current density is essential because the potential of the area to be protected doesn't reverse itself (become cathodic) until the protective current density is reached.

Protective current density depends on many factors that

**Economics.** A major question you'll face in the endless battle against corrosion is deciding how much protection is economically justified. To come up with an intelligent solution, you'll have to consult plant production people to get answers to questions like: How long will the equipment be used before it is obsoleted by more modern machines? Is equipment operated continuously or intermittently? How high is the operating temperature? Is the machine indispensable to the over-all process? What are the probable corrosives involved? You'll have to weigh all factors — tangible and intangible — in any complete economic study.

**Your corrosion-fighting arsenal** can include many of today's newest methods too. Researchers are taking giant steps in their attempts to upgrade these methods.

**Protective coatings** and paints have been radically improved with the development of new vehicles and inhibitive primers. These assure better protection on the job.

**Newer corrosion-resistant metals** and alloys can, if you apply them right, stand up under severe corrosion conditions. Naturally, they're more expensive than the less-resistant materials they replace. But their increased life span can more than pay for initial cost differences.

**Plastics,** relative newcomers to the battle against corrosion, are widely used, both structurally and as coatings.

**Cathodic protection,** still another approach to your corrosion problem, is daily proving itself a top protective weapon for pipelines, power cables, condensers, storage tanks and a host of other industrial equipment.

## Choosing the right anode—key to good cathodic protection

Once we've decided on needed current density, next step is to choose the right anodes and arrange them to distribute current to *all* parts of the structure in contact with the liquid or soil. To do the job we can use electrolytic or galvanic anodes, *diagram facing page,* or a combination of the two. In either case, right anode position, quantity, length and area in relation to the protected surface, play an important role in planning the system.

### Electrolytic Anodes

Electrolytic anodes can be expendable or non-sacrificial — both energized by an external dc source. Expendable types include iron, carbon steel, chrome steel, aluminum and graphite. Non-sacrificial designs are made of platinum.

**High-silicon cast-iron** anodes, either bare or installed with backfill, are a recent development for ground-bed (soil) installations. They resist sulfated, alkaline and most chloride-containing soils. Their best performance is at 5 amps per sq ft, and below. But even if you're faced with substantially heavier currents, anode weight loss is slow, predictable.

**Platinum** may be used in the form of a small diameter wire, or by cladding a copper or nickel rod. For protection of submerged surfaces, platinum anodes are expensive. Thus, their use is limited. Also, the economically justifiable diameter of platinum anodes often produces a large voltage drop, high power costs.

**Graphite** anodes can last for many years. So it's smart to consider them in areas where replacement is a difficult and costly process. If you're installing them in soil, manufacturers recommend a granular coke breeze backfill to allow gas formed to disengage itself from the graphite anode.

### Galvanic Anodes

Galvanic anodes are made of a metal higher in the galvanic series than the metal you're trying to protect. That's why they require no outside current source. They're always sacrificial. Common materials are zinc, magnesium, aluminum.

**High-purity zinc,** aluminum alloys do a top job in sea water. Zinc is also used for lower resistivity soils (less than about 2000 ohms per cc). Magnesium works well up to 10,000.

Relatively low driving voltages generated by galvanic anodes can be an important point in their favor. Below city streets, for instance, they're less likely to interfere electrically with nearby structures. But low voltage may limit their use where current requirements are high.

## galvanic methods fight corrosion with corrosion

vary considerably. And you can't assume that any two jobs will be exactly alike. The most important items affecting protective current density are type and condition of applied surface coating (if any), dissolved oxygen concentration, chemical analysis of the electrolyte, as well as its conductance, temperature and pH.

**Water conditions.** A 2 to 4 milliamp (ma) per sq ft current density is enough to protect a bare steel surface. This is easy to maintain in waters of average hardness. Soft water, because of the absence of dissolved salts, tends to be more electrically resistant and requires higher voltages, more anodes to produce a protective-level current. Hard water has low resistance. And if system isn't designed to operate at lowest voltage consistent with adequate protection, high current quickly consumes anodes.

**Coatings teamed with cathodic protection** can often prove most economical. Then only small areas, where faults or pinholes exist, need protection. These areas demand only a small current, radically reducing auxiliary-anode consumption.

**Type of protection,** as we've seen, can be either electrolytic or galvanic. Electrolytic protection — the impressed-current method—is commonly used where relatively large amounts of current are needed at a few locations. Galvanic techniques work best where we need to apply smaller currents at many locations. Notice that in both cases we're dealing with direct current (dc).

**Choosing the right equipment** to get the necessary power can be of prime importance. Several types of power units are available. Motor-generators, wind generators and rectifiers that convert ac to dc, are applied on electrolytic systems. Galvanic action itself supplies power for the galvanic system. To pick the right one you'll have to weigh their economic as well as technical merits.

## Cast iron, carbon steel

Relatively cheap, easy to come by, cast iron and carbon steel lead the engineering-metals field in total volume and applications — many of them corrosive.

Cast iron contains 3 to 3.5% carbon, along with silicon and other elements. Structurally it includes iron, iron carbide and free carbon (graphite).

Corrosion resistance of cast iron and carbon steel are about the same. But there are exceptions, and a look at their relative structures tells why: Carbon in carbon steel is present as iron carbide, whereas some carbon in cast iron is free graphite. Thus, gray cast iron is subject to graphitic corrosion (see page 79) in salt and mine waters and sulfate-containing soils. White cast iron is immune to such attack because nearly all its carbon is in the carbide form.

Metallurgists find that while carbon in steel has an important effect on its physical properties, it has little effect on corrosion resistance.

## Wrought iron

We single out wrought iron because, under certain conditions, it provides an economical solution to corrosion problems. Briefly, wrought iron is a two-component metal consisting of high-purity iron and iron silicate — a glass-like slag. It's the only ferrous metal that contains such a slag. The iron silicate is largely responsible for wrought iron's corrosion resistance.

Unlike either steel or cast iron, wrought iron is never cast in an ingot mold. So its structure and composition don't change near the surface. Uniformity minimizes chances of accelerated corrosion rates after material has been in service for several years.

## High-silicon irons

Ideal for corrosive conditions involving high temperature and erosion attack, these cast irons are relatively low cost. Their main alloying element is silicon — 14.5%. They also include .85% carbon, varying amounts of manganese and molybdenum.

Although high-silicon cast irons have fair tensile strength, in common with all cast irons they have no ductility. And they're prone to thermal, mechanical shock. Thus, steam tracers are commonly used with high-silicon irons to avoid too-rapid heating and cooling. When used in this way, these irons can operate in systems at as high as 1000 F without difficulty.

## Cast high alloys

Two main classes of cast high alloys are iron-chromium and iron-chromium-nickel.

The iron-chromium alloys having between 8 and 14% chromium have the characteristics of steel. They can be altered by heat treatment. Higher chrome and chrome-nickel content alloys don't show the phase changes that steel does when it's heated or cooled. Thus, they're non-hardenable. Their properties depend on composition rather than heat treatment.

Many of these alloys are used for corrosion- as well as heat-resistance. But heat-resistant types usually contain more carbon.

Corrosion resistance of equivalent wrought and cast alloy compositions are just about equal.

## Copper-bearing steels

Adding small amounts of copper to steel, can boost its corrosion resistance substantially — especially where corrosion is due to atmospheric conditions. But adding copper to steel for underwater, soil applications, usually has little effect on corrosion properties.

Adding phosphorus to copper-bearing steels shows good results too. For example, one test showed that increasing phosphorus from 0.005 to 0.070% in a 0.5% copper steel increased corrosion resistance in an industrial atmosphere about 25%.

# MODERN ENGINEERING METALS . . . weigh them

The array of metals that appears on this and the following three pages includes virtually all of the major engineering types, with these exceptions: (1) the noble metals — silver, gold, platinum (2) metals that are used mainly as alloying elements — tungsten, vanadium, molybdenum, manganese, chromium. But we mention them above, where they're added to base metals, as alloying elements, largely to improve corrosion-resisting and mechanical properties.

**Choosing the right metal.** In coming to grips with this problem, the engineer usually has little difficulty eliminating those metals which just won't do. His big problem is evaluating the finer differences that exist among the closest candidates. And often, the corrosion problem becomes the deciding factor. Other times it takes equal importance alongside such items as: (1) availability in the required forms — castings, sheet, tubes, forgings, etc. (2) ease of fabrication — machining, forging, bending, welding (3) ability to stand up under normal service stresses.

Focusing now on the corrosion factors themselves, let's see what we must consider in selecting the right engineering metal for specific applications.

## Low-alloy steels

One definition of low-alloy steels: Total alloy content is 5% max. Generally speaking, metallurgists add these elements to boost strength and toughness, rather than corrosion resistance. But corrosion resistance of most low-alloy steels is generally better than carbon steels. Anticorrosion standouts are the low-chrome heat-resisting steels commonly used for superheater tubing in boilers. These include 2%-chrome ½%-molybdenum; 2¼%-chrome 1%-molybdenum; 3%-chrome 0.9%-molybdenum. They're selected for their heat- and corrosion-resistant properties.

9%-chrome 1%-molybdenum superheater steel contains too much alloy to be called a low-alloy steel but not enough chrome to be considered in the stainless class. It's basically an intermediate alloy steel. Corrosion resistance of these low and intermediate alloy steels falls between the copper-bearing and stainless steels commonly used by industry.

## Austenitic stainless

Corrosion and oxidation resistance of all stainless is based on chromium. But nickel also plays a key role, especially in the austenitic types such as the "18-8's" with a nominal analysis of 18% chromium and 8% nickel as the major alloying elements.

The austenitic structure is responsible for the characteristics that have made the chrome-nickel stainless steels most widely used in the stainless group.

Most common 18-8's are types 302, 304. They have corrosion resistance, ductility and toughness over a wide temperature range. Type 303 is a free-machining stainless, slightly less corrosion resistant than 302.

Two new standard austenitic compositions — AISI types 201 and 202 — have recently bowed in. Corrosion-wise they're on a par with 301 and 302. But they're lower in nickel and have 5.5 to 10.0% manganese.

## Molybdenum stainless

Adding 1¾ to 4% molybdenum to austenitic stainless steels improves its corrosion resistance to a variety of acids as well as brine and sea water. This group also has the highest elevated-temperature creep strength of any standard stainless available.

Greater resistance to pitting corrosion which, as we've already seen, can occur under deposits (low-oxygen areas) that remain on stainless steels for a long time is also the result of adding molybdenum.

The basic moly stainless is type 316. A low carbon modification of it, 316L, is used where a large amount of welding fabrication is necessary.

## 12% chromium stainless

The 12% chromium stainless steels (actually between 11.5 and 14%) do an excellent job resisting atmospheric corrosion — weather and water. They're hardenable by heat treatment. And their corrosion resistance is greatest in the fully hardened condition.

Typical 12% stainless is type 410. It resists scaling (high-temperature corrosion) up to about 1200 F. So it's used for furnace parts operating below that temperature. Results are generally excellent.

Other alloys in this group are specialty grades. Type 403, for instance, is made for extra-high toughness applications, such as steam-turbine blading.

## 17% chromium stainless

Nominal 17% chromium content gives these stainless steels higher corrosion resistance than the 12% group.

Special advantage of this group is its low coefficient of expansion. Thus, if oxide scale does form, it's tight and doesn't crack off due to expansion and contraction of the metal during heating-cooling cycles.

Strength of the 17% chrome stainless types lies between chromium-nickel stainless and mild steels.

## cost- and corrosion-wise against your own special needs . . .

**First cost of the metal** is important. But considering only first cost can lead to wrong answers. A more corrosion-resistant metal at reasonably higher cost, can more than justify itself by its greater life span, higher heat-transfer rates through the use of thin-walled sections and the elimination of corrosion products that are heat-insulating.

**Major technical factors** that can influence the choice of a metal to resist corrosion include temperature, velocity, and oxidizing capacity of the atmosphere, solution, soil, etc. And we talk about these where they apply throughout this report. But there are several easy-to-overlook corrosion pointers that can, in many situations, spell the difference between the right and wrong choice. Here's the gist of them.

**Low-velocity corrosion test** data may be misleading in predicting the behavior of a material to be used for a pump, valve, heat-exchanger tube or other equipment where metal contacts a high-velocity corrosive solution.

**Vapor or gas pressure** above a corrosive liquid may have a substantial effect on corrosion by changing the quantity of oxygen or other corrosive gas that may be forced into the liquid or withdrawn from it. High pressures generally tend to aggravate corrosive

## 20 alloy

Based on its nominal composition, 20-alloy is really a nonferrous metal since it contains less than 50% iron (approximately 45%). But because of its uses and high nickel (29%) and chromium (20%) contents, engineers consider it a highly-alloyed stainless. 20 alloy comes in both cast and wrought forms.

Costwise it lies between molybdenum stainless and the Hastelloys, Chlorimets (nickel alloys). Physical properties and welding characteristics are similar to the 18-8's. Because of its austenitic structure, it can't be hardened by heat treatment.

Relatively high erosion-corrosion resistance and reasonable cost often make 20 alloy the most economical choice for pumps, valves, piping, fittings and a variety of plant-service equipment.

*Worthite*, a highly-alloyed stainless (20% chromium, 24% nickel), is similar to the 20 alloys in both composition and corrosion resistance.

## Nickel and its alloys

Nickel by itself, or alloyed with copper, chromium or molybdenum forms a broad group of engineering metals that show high corrosion resistance. Their strength and hardness are almost as great as carbon steel and they're endowed with ductility and toughness at sub-zero as well as high temperatures.

Although oxidizing conditions tend to promote corrosion of nickel, it can protect itself by forming a passive oxide film.

*Chlorimets*, containing about 60% nickel, and varying amounts of chromium and molybdenum as major alloying elements, are tops for corrosion resistance but they're relatively expensive. So you'll use them where less costly alloys will not do. They fare well in oxidizing or reducing atmospheres.

*Hastelloys* (grades B, C and D) contain anywhere from 55 to 84% nickel. Grade B includes 28% molybdenum. Grade C: 17% molybdenum, 16% chromium, 4% tungsten. Grade D: 10% silicon.

Corrosion resistance and strength at high temperatures are among Hastelloy's standout properties. And although they're expensive, they can be an economical solution to problems involving severe corrosion at elevated temperatures.

*Monel*, commercially the most important of the nickel-copper alloys (67% nickel, 30% copper), is actually more corrosion resistant — under a wide variety of oxidizing or reducing conditions — than either of its major alloying elements. And since nickel and copper are close in the galvanic series, there's no tendency to redeposit dissolved copper such as we find in the dezincification of high-zinc brasses.

*Inconel's* main alloying elements are nickel (77%) chromium (15%) and iron (7%). Even in strongly oxidizing solutions, Inconel is virtually free from attack. The reason: Chromium becomes passive by forming a protective oxide film.

High chromium content gives it the nod over nickel and monel in handling sulfur compounds and hydrogen sulfide at high temperatures.

## Aluminum

Because of its resistance to corrosion, high strength and low cost, aluminum is most widely used of all the light metals (aluminum, magnesium, titanium). It withstands atmospheres that contain sulfides, carbon dioxide, sulfur dioxide and other contaminants. Formation of an oxide barrier controls such atmospheric corrosion.

Aluminum is corrosion resistant to pure water. But even traces of copper or iron can cause it to corrode. If you're circulating water in a closed system, inhibitors such as sodium chromate prevent attack.

High thermal conductivity of aluminum boosts heat-transfer rates in heat exchangers. And high electrical conductivity combined with corrosion resistance makes it ideal for electrochemical applications.

*Clad aluminum alloys* combat pitting corrosion by offering cathodic protection to the core metal. Aluminum cladding on heat-exchanger tubes, for example, acts as the anode, deflecting corrosion away from the tube base metal. Such alloys are economical too.

# . . . but be sure to tap the many sources of outside help

attack by vapors or gases at elevated temperatures.

**Applied stresses** don't *necessarily* increase a metal's tendency to corrode. But stress effects are important. We've seen that cyclic stresses, for example, can combine with corrosion, lead to corrosion fatigue, page 79.

**Heating-cooling cycles** can change the corrosion-resisting qualities of some alloys. Thus if you plan to weld, forge or hot bend a metal that must be corrosion resistant, it's smart to consider the effects of such fabricating methods.

**Galvanic effects** are important where different metals make electrical contact in a corrosive solution. Don't forget to consider relative areas of the metals, making sure that relatively small area of the more anodic metal doesn't lead to accelerated corrosion.

**Effects of corrosion product** on the material being handled may be decisive. In steam and condensate systems corrosion products can build up, foul steam traps, valves and other small flow areas.

Complex as choosing the right corrosion-resistant metal is, remember that you can count on outside help too. Equipment manufacturers and metals producers have been in the thick of the battle against corrosion for many years. They stand ready to assist you in making the right choice.

## Magnesium

Key to controlling corrosion of magnesium: Keeping harmful impurities out of it. For example, if iron content goes from 0.005 to 0.05%, corrosion rate climbs from 30 to 100 times in salt water. Copper and nickel have similar effects. Here's the reason: These impurities act as cathodes, cause magnesium, which is at the top of the galvanic series, to act as the anode.

Most commercial forms of magnesium include small (up to 9%) quantities of aluminum, manganese and zinc to offset harmful impurities present.

## Copper and its alloys

Either in its pure form or alloyed with zinc, tin, lead, nickel, aluminum, silicon or manganese, copper has good all-around corrosion resistance. Add to this its excellent thermal and electrical conductivity and you've pinpointed the main reasons for its popularity.

*Arsenical admiralty* (70% copper, 29% zinc, 1% tin, 0.03% arsenic) shows good corrosion resistance to most waters and does a top job in sea water at velocities less than 6 fps.

Manufacturers add arsenic to the metal to inhibit plug and layer type dezincification.

*Muntz metal* (60% copper, 40% zinc) is used where corrosion resistance must join forces with high strength, moderate ductility. Common applications include condenser heads, tubes and tube sheets, baffle and support plates in heat exchangers.

*Red brass* (85% copper, 15% zinc). Because of its natural resistance to dezincification red brass is often favored over other copper alloys for heat exchangers and plumbing piping.

*Cupronickel alloys* that contain 10 to 30% nickel are often picked as heat-exchanger tubes because they resist corrosion by salt water used for cooling. More recently, engineers have been swinging over to these alloys for tubes in feedwater heaters, largely because they do a good job at high temperatures.

*Aluminum brass* (78% copper, 2% aluminum, 0.03% arsenic, balance zinc) naturally more resistant to corrosion than admiralty — both from fast-moving sea water as well as polluted waters found in harbors and rivers contaminated by sewage and wastes — has been replacing admiralty in a substantial number of installations. It's well suited to condenser tubing where inlet-end corrosion or impingement corrosion is a serious problem.

*Bronzes* generally contain significant amounts of tin in addition to copper and other alloying elements. Common types include silicon bronze, phosphor bronze and manganese bronze. Their corrosion resistance is on a par with the copper-zinc alloys.

## Zinc

Major uses for zinc in combatting corrosion are (1) Protective coatings for metals — applied by galvanizing, metallizing, sherardizing. We'll have more to say about these later. (2) As galvanic anodes, see pp 80-81. (3) As pigments for corrosion-resistant paints. These are zinc, zinc oxide, zinc chromate.

Corrosion rate of zinc in water is much lower than iron, slightly higher than copper. But, as with other common metals, temperature, pH and oxygen-concentration effects can alter the picture considerably.

## Tin

Because tin is a low-melting-point metal we don't use it where high-temperature corrosion is likely to be a problem. But it does a top job as a protective coating over steel and in such alloys as bronze.

An invisible film of stannic oxide normally covers tin. But acids, alkalies can cause pitting.

Distilled, soft tap water doesn't corrode the metal. And adding 5% antimony avoids localized corrosion.

## Lead

Corrosion resistance of lead depends on a thin protective coating — either an insoluble lead salt or a soluble film. First type resists attack even where the film suffers mechanical injury, because the environment promotes self-healing. By contrast, the soluble film can dissolve in the solution or atmosphere surrounding the lead, leave it open to corrosive attack.

Neutral solutions tend to build up the protective film (lead carbonate, oxide). Low pH solutions show varying rates of attack.

Chemical lead, acid lead and copper lead are common commercial grades. Common power-service jobs for it include: lead-sheathed cable, lead-covered pipe, gaskets and lead-clad copper heating coils.

## Tantalum

Strongly resistant to most corrosives, tantalum is used mainly for heat-transfer equipment — heating coils, coolers, instrument-bulb protection. The metal performs well even under some corrosive conditions that bar the use of gold or platinum. Thus its relatively high cost is justified on a necessity basis.

Tantalum is produced by powder-metallurgy methods. Its chemical properties resemble those of glass.

## Titanium

Relative newcomer to the metals field, titanium is one of the most corrosion-resistant metals known. It ranks among the best metals available in its ability to resist the action of sea water. And it can be heated to 1100 F without high-temperature oxidation effects.

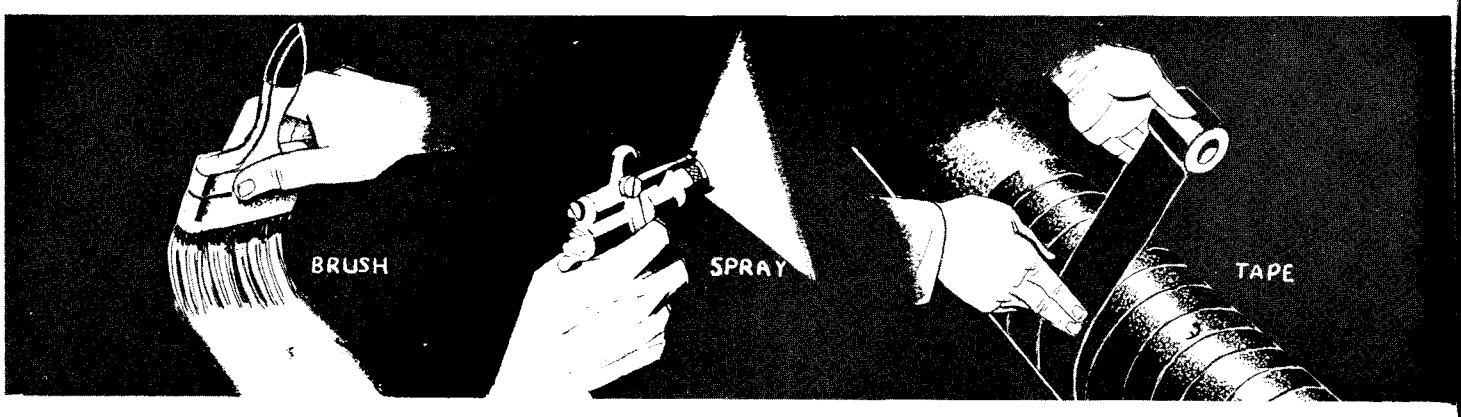
Biggest drawback of this *wonder* metal: Its inability to compete with other metals on a cost basis. But its price has been dropping steadily.

# INERT BARRIERS — organic, metallic and vitreous forms

Generally speaking, inert barriers include all organic, metallic, vitreous and wood barriers applied between metals, alloys and their corrosive environment.

Going a step further, we can subdivide organics into *coatings*, *mastics* and *linings*. Coatings are films 5 to 20 mils thick. (Corrosion engineers find that when total coating thickness is less than 5 mils it doesn't give reliable protection). Linings are films 60 mils thick and greater. Mastics fall in a range between these two.

You can use barriers by themselves or combine them with other methods of corrosion control. Often, combination control is most effective, economical. Underground




## ORGANICS — should you use coatings, mastics or linings?

Most popular weapons in the corrosion engineer's arsenal are protective organic barriers. Pictured above are the most common ways of applying them.

To get maximum service life from most coating systems, films should be applied in a minimum of three coats and, as we've already seen, be at least 5 mils thick.

**Right surface preparation** — sandblasting, etching, wire brushing — plays a key part in getting good results from organic barriers and is particularly important if you plan to use thin coatings. For most jobs best preparation is sand blasting. Resulting clean, rough surface provides excellent mechanical bonding qualities.

Barriers made from synthetic as well as natural resins are available in a wide variety of types. But as we'll see in the following sections, it's possible to classify them according to similar performance, characteristics, etc.

### Elastomers

Most important application for this group: Linings for equipment designed for highly corrosive conditions. But they're also widely used as coatings.

Made from both natural and synthetic resins, elastomers include rubber barriers — natural rubber, neoprene, butadiene-styrene rubber, butyl rubber, and nitrile rubber. Their resilience make them a good choice where abrasion and impact are likely to be doing their treacherous work hand-in-hand with corrosion.

**In selecting an elastomer** barrier be sure to investigate its bonding properties. Most of the common elastomer barriers will not adhere directly to metal. They're usually applied over a chlorinated-rubber primer.

Neoprene-based coatings—resistant to non-oxidizing acids, salts and alkalies up to 150 F — are used for lining vessels and storage tanks, especially where intricate shapes make it difficult to get full protection with a lining material. Natural rubber also fits for such applications.

### Thermoplastic

Applied thermoplastic films — vinyls, polyethylene, vinylidene chloride, saturated oils, waxes, bitumens — require no further curing after they're applied, but elevated temperature softens them.

**Vinyl material** compositions vary substantially, depending on where, how they're to be used. Manufacturers add plasticizers (to keep vinyls from becoming hard, brittle) and heat stabilizers in varying amounts to suit customer needs. Vinyls, when you apply them according to manufacturers' specs, yield a general-purpose coating that has excellent resistance to oxidizing materials.

Polyvinyl chloride (PVC), popular member of the vinyl group, is a tough, resilient barrier that you can use either as a liquid to form thin films or as sheets that can be cemented to metal's surface. PVC protective tapes can be your answer to underground pipeline protection problems.

Relatively new vinyl is a high-solids aluminum coating. Aluminum is present in finely divided particles — virtually liquid aluminum. In coating form it protects tanks, coils against the action of oils, mild corrosives.

**Polyethylene** has excellent resistance to oxidizing agents. Its versatility, low cost make it highly popular.

**Polyfluoroethylene,** one of the newer materials in this group, features outstanding chemical resistance to most corrosives up to about 500 F. But it's relatively tough to apply.

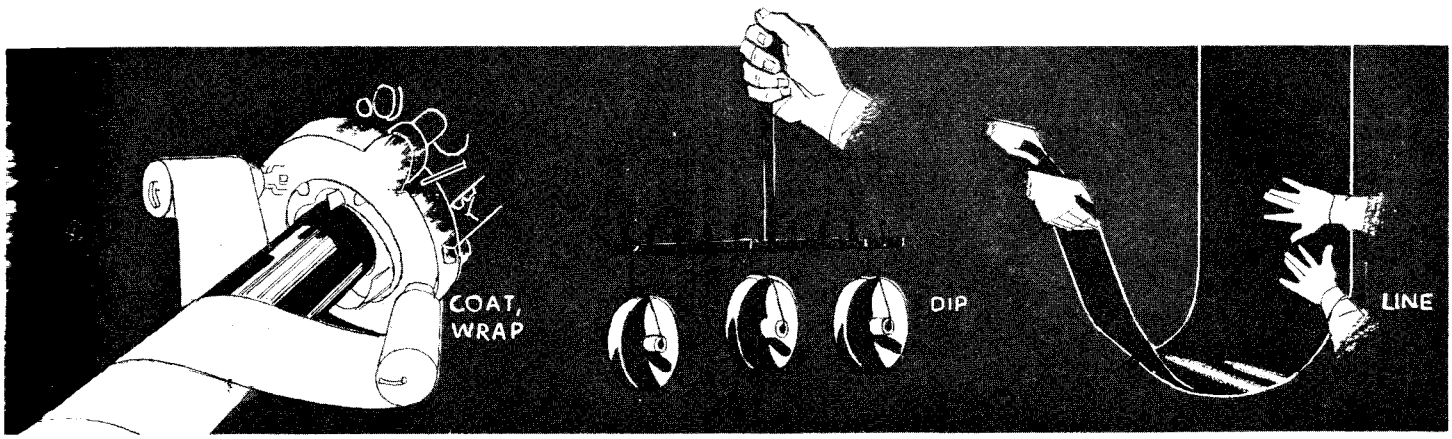
**Vinylidene chloride,** derived from ethylene and chlorine, is a highly corrosion-resistant barrier. Important application: Lining piping, tanks where corrosives are present.

**Bitumens** — either coal-tar or asphalt base — soften at high temperatures. Thus we consider them thermoplastic.

## stand between your plant equipment and corrosive attack

pipelines, for example, are coated to reduce current flow needed for cathodic protection.

**Choosing the form.** From a practical viewpoint, giving the nod to either a coating, mastic or lining boils down to pinpointing the required thickness for adequate protection. Thus, service conditions must be weighed carefully. Is the equipment subject to rough handling, abrasion? How fast will corrosion take place? (Corrosion speed is commonly measured in inches per year, ipy. Engineers consider that rates greater than 0.05 ipy indicate highly corrosive conditions). These are just a few of the important questions corrosion men must find answers to.




## Size up corrosion conditions, cost before making your choice

Both the coal tar and asphalt base types give good protection — especially for coating underground pipelines in the field. To reinforce these organic barriers against soil stresses, cloth, jute, burlap, glass-fiber tapes and other materials are wrapped between coating layers.

Another recent anti-corrosion application of coal-tar paints: Coating submersible-type transformers and network protectors where salt that's used for snow and ice removal contaminate ordinary paints.

### Thermosetting

Like the elastomers, thermosetting barriers often need further processing — baking for example — after they're applied, to develop their best properties. Thermosetting films are tough, rigid and resist high temperatures. They're highly versatile engineering materials.

**Alkyds.** These can be either thermoplastic or thermosetting. But the latter is their most important commercial form. Excellent durability under a wide range of exposure conditions makes them most popular of the resins used in protective coatings.

Alkyds are often blended with other resins to get special protective properties. So-called oil-modified alkyds (with drying oils) are quick-drying coatings that produce a good general-purpose industrial finish.

**Phenolics** have been a mainstay of industry for many years. Major types are: (1) baked (2) air-dried.

Baked types are heated to about 350 F after applying them. Because specialized equipment, experience is a must in turning out good baked phenolic coatings they're normally applied by specialists in well-equipped shops.

You can consider using phenolics up to 350 F, except where oxidizing agents are present. Tanks, vessels protected by such baked coatings can be steam cleaned.

Brittleness — until recently a major defect of baked phenolic coatings — can now be overcome by epoxy-phenolics.

**Epoxy resins** — comparative newcomers to the field — are much like the phenolics. And engineers are using them in substantially the same way. They have good corrosion resistance in both baked and air-dried forms.

Major advantage is their greater range of corrosion resistance than the phenolics. Also important: They have excellent flexibility and bonding properties.

**Oleo-resinous materials** are really a special class of thermosetting barrier that's formulated from natural rather than synthetic materials. A drying oil is the ingredient common to all types in this group.

Most important oleo-resinous materials from the plant engineers' viewpoint: oil-base paints. They're relatively low cost, easy to apply, can build up to the minimum 5 mil thickness in fewer coats than the average synthetic. And they possess excellent resistance to weathering. Thus, they're favored for general outdoor anti-corrosion maintenance.

Corrosion-inhibitor pigments such as red lead, white lead, zinc chromate, iron oxides, zinc oxides and aluminum powder fortify many of the oleo-resinous paints for corrosion combatting applications in the plant.

**Silicones** and their various modifications have moved into the corrosion picture in a big way only within the past few years. And they're fast winning favor among corrosion engineers — especially for high temperatures.

Silicone varnishes have been pigmented with aluminum powder to protect steel surfaces at temperatures to 1000 F. They've successfully protected steel stacks for many months at 400 to 800 F. where other organic finishes failed.

Combining silicones with alkyd, phenolic, amine resins yields a finish that's less brittle, more adhesive to steel. But these combinations generally have somewhat lower heat resistance than the straight silicone barriers.

# METALLIC COATINGS — how you can get lower-cost protection by using higher-cost metals

When you need the protection afforded by expensive, often hard-to-come-by metals but can't justify them costwise, metallic coatings are a likely answer to your problem.

A wide variety of metallic coatings are available commercially. But not all of them are applied primarily to resist corrosion. In the paragraphs that follow we limit ourselves to the common types that are used mainly because of their anti-corrosion properties.

## ZINC

Zinc coats on steel take on a dual function: First, they keep steel from rusting by preventing contact with corrosive atmospheres—outdoors as well as indoors. Second, zinc protects the base metal by cathodic protection.

Metal's low melting point allows it to be conveniently applied to steel in controllable thin coats at low cost. Thus, it's applied in several different ways: hot-dip galvanizing, electroplating, spraying (metallizing), cementation (Sherardizing) and vapor condensation.

While zinc does a first-rate job resisting atmospheric corrosion (an average 2-oz-per-sq-ft surface coating lasts about 15 years in a highly industrial atmosphere) it's not frequently used at 450 F or above. And strongly acid or alkali conditions cut its life expectancy substantially.

## NICKEL, CHROME

Nickel and chromium coatings find widest use where they must not only resist corrosion, but maintain lustre.

Protection you'll get from these coatings varies with their thickness, nature of the base metal, type of corrosive atmosphere, thickness being the chief factor. 0.5-mil thickness in mild atmospheres is roughly equivalent to 2.0-mils in industrial areas. A 1.2-mil coating on steel does about the same job as 1.0 mil on zinc or 0.4 mil on brass.

Coatings tend to be porous if they're less than 1.0 mil, exposing the base metal intermittently. When atmosphere attacks the metal, porosity increases, making the base metal an easier target for corrosion.

Copper undercoats reduce plating costs. But they don't offer as much protection as the same thickness of nickel. Their value varies with different atmospheres, thicknesses.

Electrolytic nickel-clad steel plate, with coating thickness anywhere from 0.006 to 0.020 inches, is moving into the fabricated industrial parts picture in a big way. Corrosion-wise, clad steel shows many of the same properties as solid nickel — and at substantially lower cost.

Chrome coatings usually have a nickel undercoat to improve corrosion resistance, reduce costs.

## TIN

Hot-dipped tin coatings on steel sheets account for the bulk of tin used in the U.S. Resulting *tin plate* goes almost entirely into cans. But tin coatings on iron and steel also hold down important anti-corrosion jobs in industry.

The usual hot-dip process yields coats that are 0.5 to 1.0 mil thick. Electrolytic techniques, because they do a better job controlling thickness, produce coatings as thin as 0.015 mil. In either case rusting can start at tiny breaks (pinholes) and spread. Thus, if you're considering tin coatings that must stand up for long periods, even in mildly corrosive atmospheres, be sure coating thickness is enough to keep pinholes to a minimum. Good practice on many industrial jobs calls for 2 to 5 mils.

### ANODIC COATINGS . . . getting protection with oxide films

Neither metallic nor paint, these coatings have made their mark within the past few years. Most important and widely used of this type is the oxide film that forms on aluminum when it's treated electrochemically. Although the oxide film that results is much like the natural oxide film normally found on aluminum, the anodic coating is thicker, provides more corrosion protection.

One of the chief uses for these coatings: Providing a base for paints, lacquers.

Anodic coatings on magnesium and zinc offer less protection than those on aluminum.

## CADMIUM

In much the same way as zinc, cadmium performs a dual-protection role: It acts as a barrier and, to some extent, it supplies cathodic protection.

$SO_2$ and $SO_3$ in the atmosphere severely corrode cadmium plating. Ammonia fumes and hydrogen sulfide can also break down cadmium — especially where humidity is high.

## LEAD

Compared to other inexpensive coating metals, lead's big advantage for above-ground corrosion problems is its resistance to a variety of acids and brines. Engineers use it to line process tanks, piping, pumps and other equipment.

Lead's ability to resist soil corrosion depends largely on minimizing porosity. Thus, thick lead sheaths — commonly used on underground cable — show good resistance in a variety of soils that attack thin coatings. To get good results with lead coatings underground, soils need to be well drained, have relatively high resistivity.

## ALUMINUM

Aluminum coatings provide a barrier against corrosion by forming highly resistant oxide films on their surfaces. Once the film establishes itself oxidation tapers off rapidly. And breaks in the film are self-healing.

Important job for these coatings: Protecting ferrous metals at relatively high temperatures.

Aluminum cladding — forming a layer of protective aluminum over the base metal by hot rolling a bi-metal ingot — produces a corrosion-resistant barrier that's always anodic. So even exposed points get cathodic protection.

# VITREOUS BARRIERS—porcelain enamels resist corrosion to 1000 F, ceramic coatings to 2000 F as today's temperature frontiers move up

Porcelain enamel and its high-temperature twin, ceramic coatings, form a group of inert barriers that may fit into your corrosion-control program in several important ways: The porcelain enamels (also called glass linings) do a top job protecting equipment from attack at temperatures to 1000 F. Ceramic coatings work well to 2000 F. They can be instrumental in giving added life to expensive metals. Or, by using these coatings, you may be able to substitute a lower-cost metal for one you're now using.

**The acid resistance** of porcelain enamel is a pretty good indication of its resistance to corrosion in general. With the right type, you can ward off the corrosive effects of practically all acids except those that dissolve silicates, the basic material from which porcelain enamel is made. That's why these barriers are widely used to line heat exchangers, storage tanks, pumps and a host of other industrial service equipment.

Vitreous barriers go back many years, even to ancient times. But they first moved into the industrial picture about 100 years ago. Cast iron provided the base metal in those days and it still looms large today as a porcelain-coated material. But new metals — mainly steels — and applications have since added to the versatility of glass linings.

**The wet process** applies the barrier to the metal as a slurry by dip or spray. Dry process, used only on castings, applies the coating as a powder. Crucial factor in both of these processes: Making sure metal to be covered has few, if any, surface defects that can cause headaches during firing.

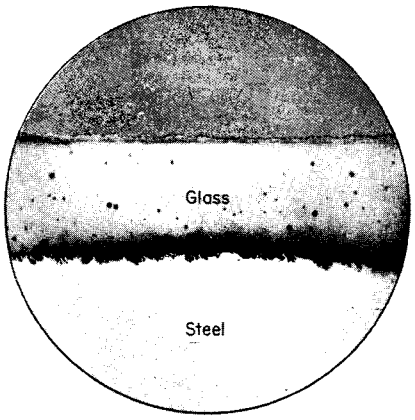
**After barrier is applied,** its *fired* at temperatures as high as 1650 F for several minutes or more. Exact temperature, time depends on barrier used, metal thickness, where it will be used. Barriers go on in one or more layers and each one is fired separately.

Life you can expect depends, largely, on choosing the right coating to suit your needs and avoiding mechanical injury, chipping for instance, to it. With reasonable care, vitreous materials can last many years.

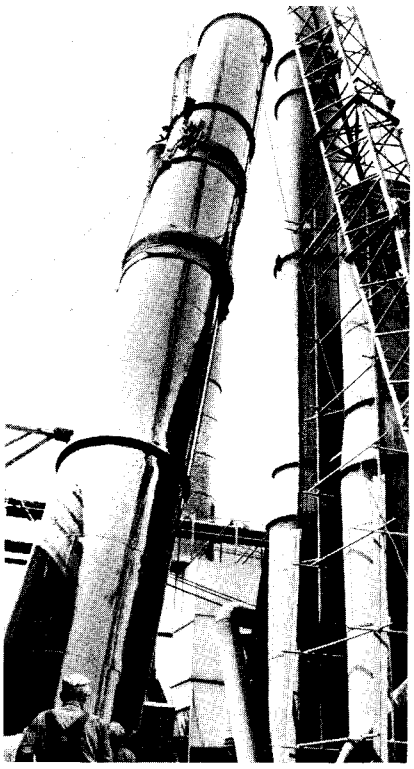
**Bonding.** While there's less than full agreement among the experts on the mechanism of coating bonding to the metal we can, for all practical purposes, say that it's a combination mechanical-chemical action. The enlarged (200 diameters) view of glass lining bonded to steel, *top right,* shows that the two are inseparably fused.

**Refractory ceramic coatings'** job is to protect the high-temperature alloys from high-temperature oxidation, a form of corrosion we talked about on page 78. Upper limits for such coatings are pushing beyond 2000 F in the gas-turbine field.

In addition to their corrosion resistance, the ceramic coatings can take thermal shock, resist chipping, cracking, blistering and erosion by high-velocity hot gases. But to develop best properties many of these coatings must be extremely thin—a few thousandths of an inch or less. So controlling their thickness is critical.




**THE INSEPARABLE BOND that forms between glass lining and steel depends largely on combined mechanical-chemical action. But experts differ on the mechanism that causes the coating to adhere**



## Glass linings are proving themselves on steel stacks

The glass-lined — inside and out — steel stack being installed above has been in service more than two years. And results thus far point up its excellent possibilities.

The glass coating eliminates accelerated corrosion engineers often run into at low flue-gas temperatures. And, compared to brick-lined stacks, they're considerably lighter. Thus, foundation and support requirements are less.

Present cost of the glass-coated stack is about 50% more than for an unlined steel stack. But expected life jumps approximately 100%.

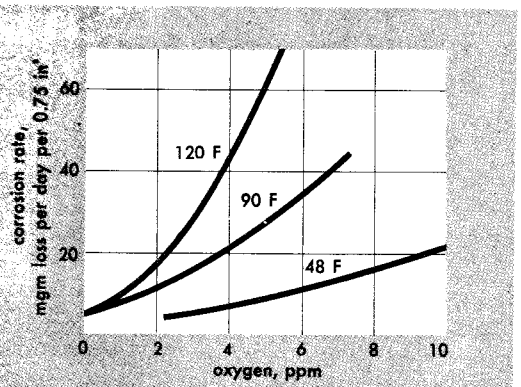
## Glass as a piping material

While glass has some obvious natural limitations as a piping material it also has some big advantages. Its corrosion resistance, under a variety of conditions, is excellent.

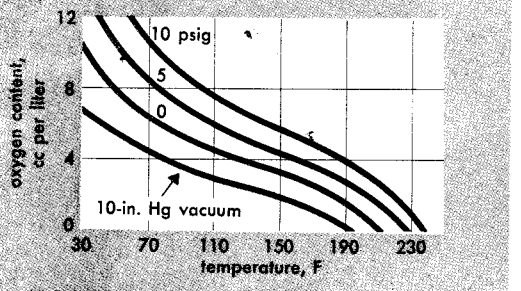
Although glass is attacked by water at temperatures greater than 300 F, temperature isn't a bar to satisfactory service. But high-temperature combined with high-alkalinity can be a headache.

Today's glass piping is making sizable gains in the food, pharmaceutical and chemical process industries — largely because of its corrosion resistance. It's available in standard sizes from one to six inches.

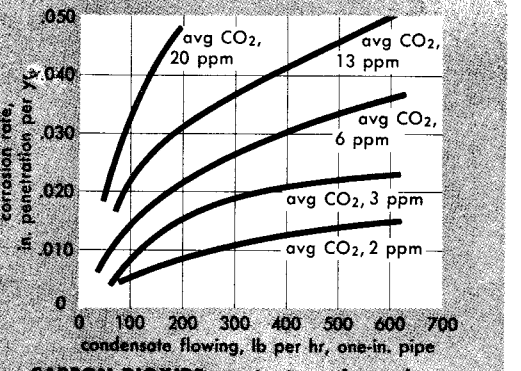
# TAMING THE CORRODENT— part of a two-pronged



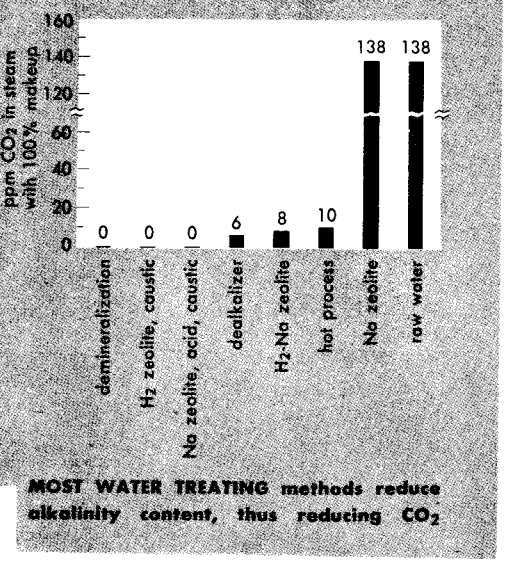

**OXYGEN-CONCENTRATION effects on corrosion rate at various temperatures**




**OXYGEN SOLUBILITY in water at different temperatures and pressures**




**CARBON-DIOXIDE content and condensate flow affect the rate of corrosion**




**MOST WATER TREATING methods reduce alkalinity content, thus reducing $CO_2$**

So far we've talked about ways of warding off corrosion by improving the metal's ability to resist corrosive attack — either by cathodic protection, alloying elements, organic, metallic and vitreous barriers. Now we go at the problem from another angle: Taming the attacking medium. This approach applies mainly when we deal with liquid-media corrosion problems. And, often, we team it up with techniques already discussed.

## Eliminate dissolved oxygen

Corrosion fundamentals, pages 74-77, showed us how oxygen attacks metals, reacting with hydrogen at the cathodic surface, forming water and depolarizing the surface, permitting additional metal to dissolve. Graph, *top left,* shows the effect of oxygen concentration on low carbon steel at different temperatures. Notice that while the effects of oxygen are relatively mild at lower temperatures, corrosion rate more than doubles when temperature goes from 90 to 120 F.

Chief source of dissolved oxygen in water is the atmosphere. Deep well waters are usually devoid of oxygen, while most surface supplies are saturated with it.

**Solubility of oxygen** in water depends on temperature and pressure. Graph, *second from top, left,* points up their combined effects: (1) Increased pressure increases oxygen solubility. (2) Increased temperature lowers oxygen solubility. We use these facts in reducing water's oxidizing capacity. Here's how:

**Deaeration,** the removal of dissolved gases such as oxygen and carbon dioxide, raises water to its saturation temperature corresponding to deaerating pressure. Deaerating heaters are designed to mix water with scrubbing steam. They also vent released gases.

Principle deaerating heaters are the tray, spray-reboiler and jet-atomizing types. But sometimes, in central-station operation, we deaerate in surface condensers that have deaerating hot wells. Condenser spills condensate into hotwell through a steam atmosphere.

**Sodium sulfite,** a chemical deaerant, combines with oxygen, to form sodium sulfate. Reaction is a fast one at 212 F and above. Thus we feed sulfite to boiler water. Best pH for this reaction is 9.0-10.0.

**Hydrazine,** a reducing agent that's been getting much attention recently, reacts with oxygen, forming water and nitrogen. Advantage of this material: no additional salts form in the reaction. (For more info on hydrazine see Power, Nov. 1956, pages 80-82.)

## Reduce carbon-dioxide content

Oxygen is roughly five to ten times more corrosive than carbon dioxide. But the two gases acting together are 10 to 40% more corrosive than the same quantity of the two gases acting separately.

**Carbon dioxide** dissolved in water forms carbonic acid, a relatively unstable compound. Only in the form of carbonic acid can a gas solution pressure be exerted — a necessary condition for removal of free carbon dioxide by deaeration. Thus, most efficient carbon-dioxide removal requires lower (more acidic) pH values.

Chief source of carbon dioxide in condensate is the bicarbonate and carbonate alkalinity of boiler makeup water. High temperatures cause them to decompose and liberate carbon dioxide that becomes entrained in steam.

Curves, *second from bottom, left,* show that when other conditions are constant, corrosion is proportional to carbon dioxide concentration of condensate. Even up to 5-ppm carbon dioxide, corrosion generally isn't serious. A close look at the bar graph, *bottom, left,* shows that several water-treating methods can meet these requirements by reducing alkalinity.

**Alkalies and phosphates** have limited application for neutralizing

# attack on your corrosion problems

Is changing the environment a better way to handle corrosion problems than protecting metal likely to be attacked? There's no pat answer. It's largely a question of economics and technical requirements of the power service or process. But the methods we highlight below represent generally accepted practice. For more detailed info, see Power Special Report, "Fundamentals of Feedwater Treatment," December 1947.

carbon dioxide in steam. Difficulty in evenly dispersing the treatment throughout steam, and objection to adding inorganic solids are drawbacks.

**Ammonia** neutralizes carbon dioxide in central-station systems with low makeup. It's fed as ammonium hydroxide or ammonium sulfate. Ammonia can do a good job in protecting ferrous metals. But copper and zinc bearing materials are likely to corrode.

**Neutralizing amines** (cyclohexylamine, morpholine) can safely neutralize carbonic acid. Unlike ammonia, the amines in low concentrations aren't corrosive to copper, zinc. Their main limitations: (1) They provide no protection against oxygen attack. (2) They're relatively high cost.

**Filming amines** (octadecylamine, dioctadecylamine) deposit a protective non-wettable film on the metal's surface. Thus, they protect against oxygen as well as carbon dioxide attack. And film doesn't break up during short periods when you must interrupt treatment.

## Keep pH within right limits

At pH values below approximately 4.5, free mineral acidity exists and can cause serious corrosion. Waters saturated with acid drainage, for example, are highly corrosive. So neutralizing them before use is essential. But in the range of most natural waters, especially where oxygen is present, pH isn't the controlling factor. Graph, *top right,* shows that when we eliminate carbon dioxide and effects of other contaminants, corrosion rate of pure zinc is low when water is between pH 6-12.

**Soda ash and caustic soda** are alkalies that neutralize acidic characteristics of boiler feedwater. Except in special cases of high-pressure boiler operation, chemical consultants recommend pH of approximately 10.5. But by treating for scale, sludge, you maintain correct pH automatically.

## Control humidity

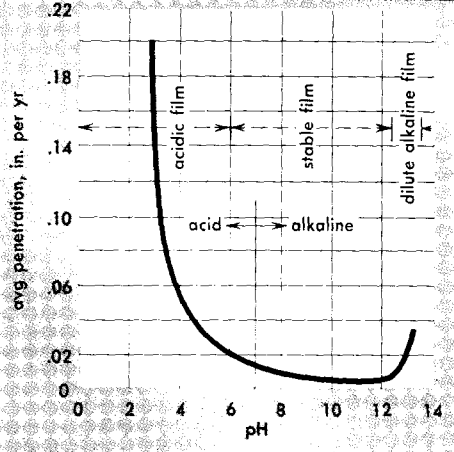
While reducing humidity doesn't fall under the heading of liquid-media corrosion problems we include it here because it *does* change the metal's environment.

Except at elevated temperatures, clean dry air doesn't corrode metal. Moisture and / or contaminants are essential ingredients in the corrosion process. Graph, *second from top, right,* shows results of atmospheric corrosion tests on mild steel. Critical relative humidity is in the neighborhood of 65%. Above this figure corrosion rate climbs rapidly — especially where other impurities are present. Thus, air conditioning is the corrosion engineer's ally.

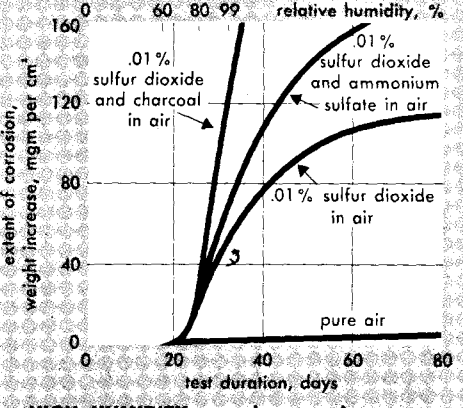
## Cut back liquid's speed, temperature

Trimming liquid temperature and speed can go a long way toward minimizing corrosion. Two lower graphs, *right,* show trends. Velocity curve plots a test on water at 120 F. Higher liquid speeds boost depolarizing effect by bringing larger quantities of oxygen into contact with the cathodic surface.

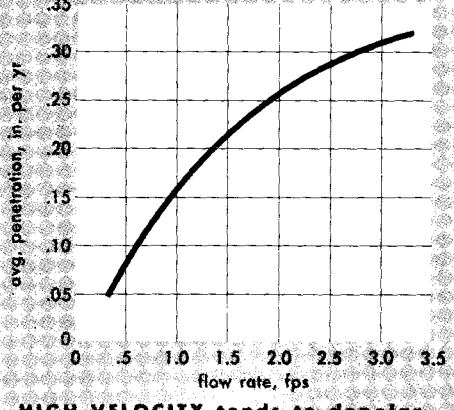
Notice, on bottom graph, that in systems where oxygen is free to escape, temperature effect is less severe. At saturation temperature, corrosion rate dips sharply.



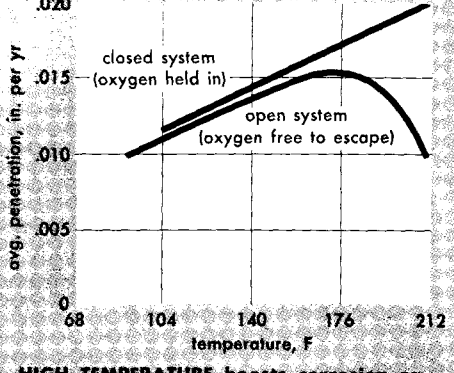

**CORROSION RATE is low over wide pH range when corrosive gas isn't present**




**HIGH HUMIDITY speeds corrosion, especially when the air contains contaminants**

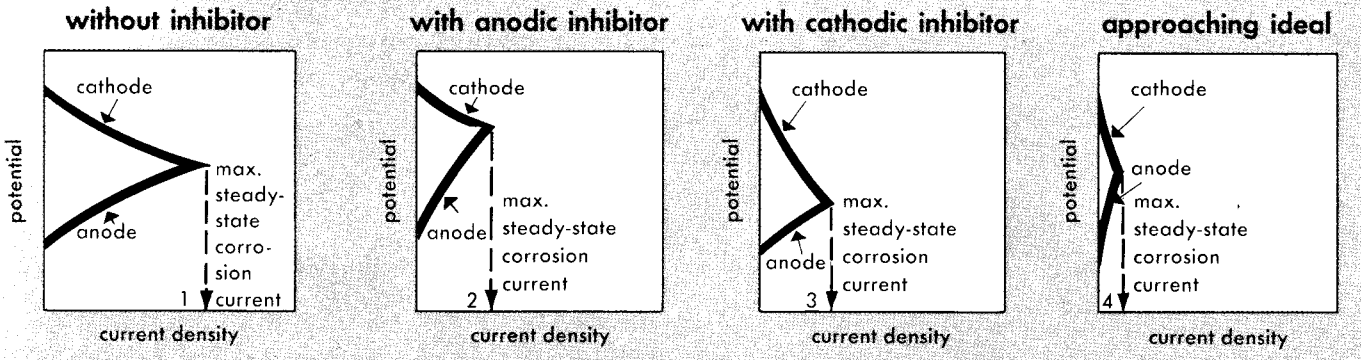



**HIGH VELOCITY tends to depolarize metal, thus increasing corrosion**




**HIGH TEMPERATURE boosts corrosion except where oxygen is free to escape**

## How inhibitors polarize corrosion cells




# INHIBITORS—these chemical compounds control corrosion by polarizing anodes or cathodes—or both

We talked about some inhibitors of importance to power men when we considered ways to protect against carbon-dioxide attack. Here we'll consider inhibitor use—inorganic and organic—as a major technique of the corrosion engineer. Inhibitors are especially important in water-supply systems, circulating-water systems for cooling and air conditioning, steam and condensate lines, brine systems.

**Inhibitors are classified** in various ways, depending on which yardstick you want to use. On the basis of their chemistry they're inorganic (sodium dichromate, sodium nitrite, etc.) and organic (glucosates, amines, phenylhydrazine, etc.). According to polarizing action they're anodic (phosphates, chromates, etc.), cathodic (arsenic and nickel salts, etc.), or general (gelatin). By application they're divided into brine inhibitors (sodium dichromate), water inhibitors (phosphates, silicates), antifreeze inhibitors (sodium tetraborate), steam-condensate inhibitors (amines, hydrazine, sulfites, phosphates, etc).

Inhibitors generally retard corrosion by increasing polarization rate at either the anode or cathode metal—or both. Anodic types polarize the anode—they shift anode potential toward that of the cathode. Cathodic types take the reverse approach. Inhibitors can also do their job by building up an electrically resistant film in the conduction path between anode and cathode.

**A close look at the graphs** above shows how anodic, cathodic inhibitors affect corrosion. We've already seen, page 77, that when current flows in a galvanic or electrolytic cell, anode and cathode potentials tend to shift toward each other. Corrosion current density, 1, corresponds to maximum possible corrosion rate without inhibitors. A compound that can boost polarization at the anode moves limiting corrosion current density to 2, thus reducing corrosion rate. We can get the same effect by increasing polarization at the cathode, 3. Corrosion would be completely stifled if anode, cathode potentials converged at negligible current density, 4.

**Anodic inhibitors,** if they're not used right, can actually accelerate corrosion. Here's how: In talking about fundamentals, page 77, we saw that corrosion rate is proportional to current flow per unit area. If it's proportional to the anode area (anode control), drop in corrosion rate depends on how much of anode area is polarized. But if current flow is limited by cathode area (most common corrosion type) corrosion isn't affected by decreasing the anode areas. Thus, if you use an anodic inhibitor in low concentrations, it may not be sufficient to protect the entire surface. Result: Concentrated pitting.

### Inorganic inhibitors and corrosion systems in which they are effective

| Inhibitor | Approximate inhibitor concentration, % | Corrosive environment | Metallic system |
|---|---|---|---|
| Glassy phosphates | Small amount | Water systems | Steel |
| Potassium dichromate | 0.05-0.2 | Tap water | Iron-brass |
| Potassium dihydrogen phosphate + sodium nitrite | Small amount + 5 | Sea water | Steel |
| Potassium permanganate | 0.10 | 0.30 N NaOH solution | Aluminum |
| Sodium benzoate | 0.5 | 0.03% NaCl solution | Mild steel |
| Sodium carbonate | Small amount | Gas-condensate wells | Iron |
| Sodium chromate | >0.5 | Cooling water | Electrical rectifier systems |
| Sodium chromate | 0.07 | $CaCl_2$ brine | Cu, brass |
| Sodium dichromate | 0.025 | Air-conditioning water | Air-conditioning equipment |
| Sodium dichromate + sodium nitrate | 0.1 + 0.05 | Water | Heat-exchangers |
| Sodium hexametaphosphate | 0.002 | Water about pH 6 | Lead |
| Sodium metaphosphate | Small amount | Ammonia | Mild-steel condensers |
| Sodium nitrite | 0.005 | Water | Mild steel |
| Sodium nitrite | 20% of sea water | Sea-water/distilled water mixtures | Mild steel |
| Sodium orthophosphate | 1 | Water pH 7.25 | Iron |
| Sodium silicate | Small amount | Sea water | Zn, Zn-Al alloys |

# TEMPORARY PROTECTION—how to combat corrosion of metal parts during shipment and storage

In a class by themselves because their chief job is to protect all kinds of fabricated metal parts while they stand idle during storage, shipment and between manufacturing steps, temporary preventives are an indispensable tool of the corrosion engineer. Actually, tagging them "temporary" is misleading because their protective qualities may be equal or superior to permanent coatings during their applied life.

**Essential features** of any temporary preventive: It must be easy to apply, and even more important—easy to remove. While it's on the metal it must stand guard against the corrosive effects of humidity, fumes, fingerprints, weathering and water. These coatings also prevent mechanical damage—nicks, burs—and preserve metal's original appearance.

The major preventives include (1) grease types (2) oil types (3) solvent types (4) strippable plastic types. Each has special advantages, limitations.

**Grease preventives** are thick-coat compounds that won't melt or flow at ordinary room temperature. Materials range from soft petrolatums to hard wax-like compounds. Softer coatings are for moderate shipping and storage temperatures. Harder coatings stand up under higher temperatures.

Dipping in heated tanks is the usual way of applying the greases. And, except for some hard *solvent-drying types*, they require the most time and effort to remove.

**Oil preventives** include the non-drying, non-setting oils of various viscosities. But even with the heaviest of these oils, protective films won't be thicker than .0002 in. And they attain final thickness by draining only—without setting or drying.

**Solvent cut-back preventives** can be subdivided according to the solvent and material dissolved in it.

(1) *Dry-type films: asphaltic resin and waxy.* These are thin, fairly hard films that look like varnish. They're on a par with protection you'll get from heavy greases. And they withstand abrasion, handling.

(2) *Water-displacing:* These usually contain substantial amounts of soap-like materials that actually remove droplets of water from metal surfaces by "preferential wetting." Preservatives' attraction toward the metal surface is greater than that of water, displacing the water. Big reason for their use: They save time, labor by permitting the easy preservation of wet parts in one simple dip.

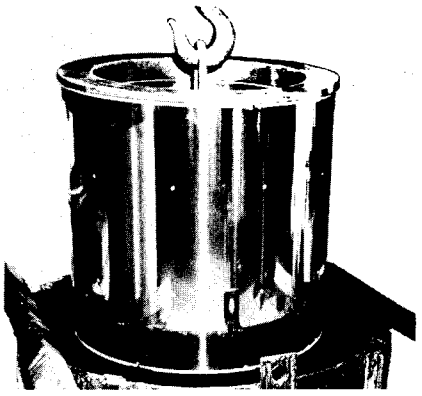
(3) *Fingerprint removers:* These contain water, an organic solvent and preserving additives. After fingerprint residues—acidic organic materials, salt, etc.—are dissolved, the additives form a protecting film. For long-term storage remove this film and replace it with a more lasting preservative.

(4) *Combination solvent preservatives:* Solvent is combined with either an oil, grease or wax-type preservative. If solvent content is low and you spray or brush it on, final film is relatively thick—comparable to greases. But, more often, these films are thin.

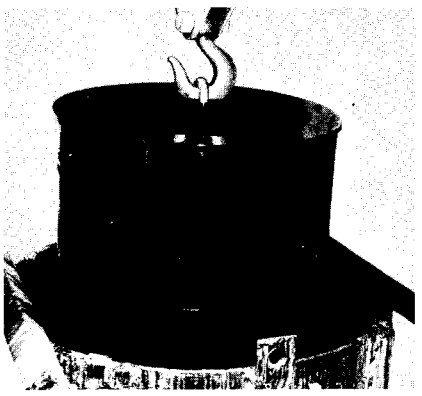
(5) *Water soluble compound* is a low-cost coating from which the water evaporates, leaving an oily film.

**Strippable plastics** are a combination of special oils, plasticizers, inhibitors, synthetic resins and plastics. Coatings are thick, from .050 to .100 in. And they have several unique features: They'll give you top corrosion as well as mechanical protection. And you can easily remove them by slitting and peeling. These coatings are applied from hot tanks.

**First essential step,** before you can use any of these coatings is thorough cleaning of the metal. Here are common ways: (1) Mechanical—sand blasting, tumbling, shot blasting, scratch brushing. (2) Chemical—solvents, alkalies, emulsions, electrocleaning.



**BEFORE: Bearing sleeve about to be dipped in solvent preventive, will be stored for many months before use**



**AFTER: Solvent preventive not only wards off rusting but won't scrape off when sleeve is assembled for shipment**

## CONSIDER THESE POINTS . . .

### Before choosing a cleaner

- What kind of dirt do you want to remove?
- How clean must metal be?
- Will cleaner chemically attack the metal?
- Are there any major safety hazards involved — fire, toxicity?

### Before choosing a preventive

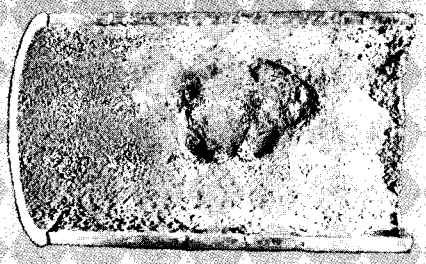
- What are storage conditions like—temperature, humidity?
- How long must corrosion protection last?
- What facilities do you have for applying, removing coatings?
- What about functions other than protection —lube qualities?

# Now let's put anti-corrosion tools to work

Having viewed most of the major weapons available to combat corrosion we're in much the same position as the general who must decide where to use his heavy artillery and where to use his infantry—and how one can best back up the other.

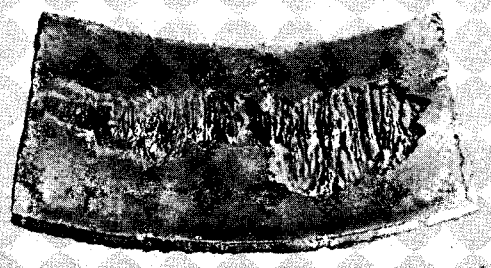
In getting the most from our corrosion arsenal we must decide whether corrosion-resistant metals alone can beat off the attack or whether they must be backed up with inert barriers. Is it smart tactics to go along with cathodic protection? If so, to what extent? To come up with the right move we—like the general—must know our enemy. What's more, we must know how he'll act under specific battlefield conditions. Our battlefields are the steam and condensate systems, cooling-water systems, combustion systems and a host of other likely targets for corrosion.

In the next ten pages we'll get to know how the enemy acts under a variety of field conditions. And we'll see which weapons give us an effective defense. In considering them we'll take into account economic as well as technical requirements that need to be weighed carefully.



**OXYGEN PITTING** is caused by liberated air bubbles that attach themselves to metal, start localized attack

**GROOVING, PITTING** in this condensate return line is due to action of carbon dioxide in dissolved form



**HEATER FAILURE** due to combined erosion-corrosion. High-speed steam prevented buildup of protective rust

## Corrosion in steam and condensate systems . . .

As operating temperatures and pressures for power-service equipment continue to climb, corrosion problems in steam and condensate systems become more complex. And — if you ignore them — they become more costly.

**Common chief offenders** when it comes to steam and condensate return-line corrosion are oxygen, carbon dioxide and ammonia. But they must be in solution before they become aggressive. Other influencing factors are condensation rate, contact time, temperature, galvanic action, low pH.

**Oxygen** in steam and boiler feedwater can stem directly from the water itself or it can enter at various points in the condensate system. Good practice calls for heating makeup water to its saturation temperature in a deaerating heater, lowering oxygen's solubility (see curves, page 90). Separated oxygen is vented. Deaerating heaters can remove virtually all oxygen.

In vacuum return systems or in gravity systems, oxygen can infiltrate. Even where the system is under pressure, oxygen finds its way in during down time.

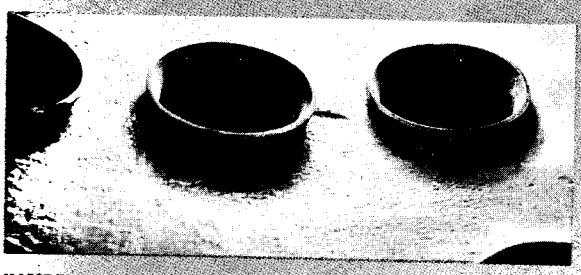
**Cooling water,** often injected into vacuum pumps to lower condensate temperature, usually contains substantial amounts of dissolved oxygen. Controlling water temperature thermostatically keeps oxygen to a minimum. Also, catalyzed sodium sulfite can be injected. It reacts with oxygen, eliminating it from cold water.

**You can spot carbon dioxide**—the usual cause of steam and return line corrosion—by its general thinning of the pipe wall or grooving along the bottom. The chief source is the bicarbonate and carbonate alkalinity of makeup water.

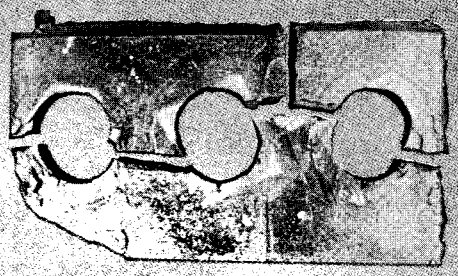
**Today's thinking** on handling the $CO_2$ problem takes a variety of forms. Hot lime-soda or lime-gypsum softening reduces alkalinity to the 40-50 ppm range—mainly in the carbonate form. Using hot lime-hot zeolite reduces $CO_2$ further by minimizing alkalinity of the softener effluent. Reducing alkalinity to the 20-30 ppm range is common practice.

Systems that operate "cold" and that can reduce or virtually eliminate carbon dioxide are (1) sodium zeolite, followed by acidification, degasification and neutralization (2) acid zeolite followed by neutralization (3) split-stream combination of sodium and acid zeolites followed by degasification (4) sodium zeolite-chloride, commonly called dealkalization, and (5) demineralization, with degasifier between acid and basic-ion exchangers.

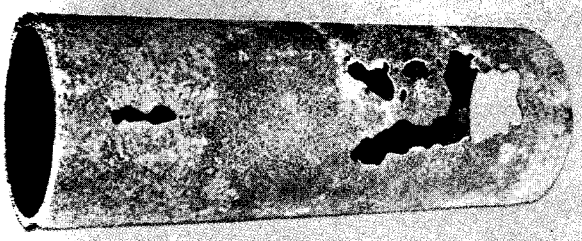
You can, by choosing the right external treatment process, bring $CO_2$ down to about 5 ppm or less. At this level corrosion generally won't be serious. But before you get too wrapped



**INSIDE BOILER DRUM** view shows formation of oxygen pits. Corrosion is likely where circulation is sluggish

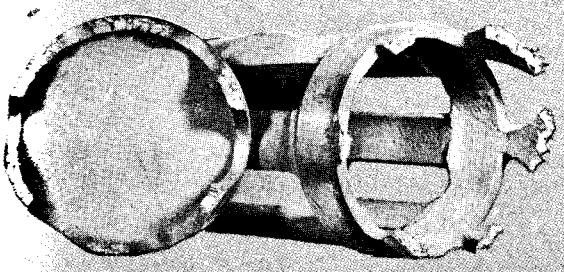


**INTERCRYSTALLINE CRACKING** of boiler drum section is due to uncontrolled caustic soda in feedwater

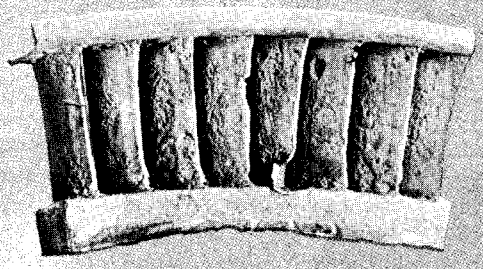


**GENERAL THINNING** of condensate line can eventually eat through pipe. Carbon dioxide was culprit here too

**ANOTHER WAY** to spot carbon dioxide grooving attack: It's invariably on bottom of pipe where water digs in



**STRESS CORROSION** cracking caused feedwater regulator failure. Changing heat treatment solved problem



**TOO MUCH MOISTURE** at turbine's low-pressure end caused combined erosion and corrosion of the blading

# what it looks like . . . what you can do about it

up in removing the last traces of residual $CO_2$ take a good look at the economics. Extreme refinements in external treatment may not be justified, especially if you plan to team it up with internal treatments — injecting amines directly to the boiler for example. Many of the inhibitors we talked about on page 92 apply to $CO_2$ control.

**Another approach** to licking the $CO_2$ problem and condensate-system corrosion in general: Backing up good chemical treatment with right choice of piping material. The Code for Pressure Piping, published by The American Society of Mechanical Engineers is an excellent guide.

Swinging over now to steam-generating equipment, corrosion and pitting usually mean that low pH and dissolved oxygen have been at work. Sodium sulfite is the reducing agent that's generally favored to remove oxygen in the boiler because it's low cost, easy to handle, and doesn't form scale. Other chemicals—organic colloids, hydrazine—can also do a good job. (See page 90 for more info on pH, oxygen).

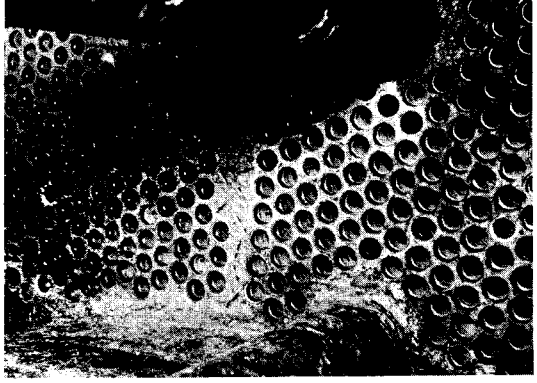
**Recirculating boiler water**—about 1 or 2%—and returning it to the boiler-feed line — either before or after the boiler-feed pump — boosts alkalinity, provides an added measure of protection against corrosion. It's often used on low-makeup systems.

**Intergranular corrosion,** also called intercrystalline cracking or caustic embrittlement, attacks welded-drum boilers at rolled-in tube ends. On riveted construction, seams are a likely weak spot. Engineers tag this corrosion form caustic embrittlement because sodium hydroxide (caustic soda) in boiler water is its chief cause. Also, it appears as a brittle fracture.

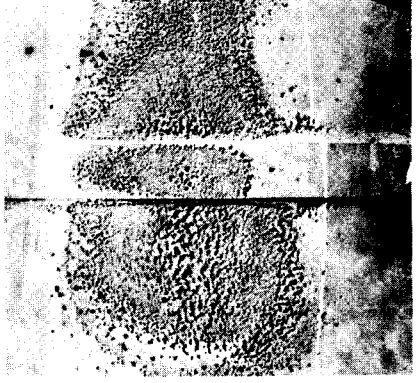
Conditions promoting embrittlement are (1) boiler-water leakage (2) high stresses due to cold working of the metal or expansion and contraction (3) water chemically attacking metal. Engineers haven't come up with a cure-all that will handle every embrittlement condition. So licking the problem depends on carefully matching conditions in your boiler to available control methods: pH-phosphate control, sodium nitrate, tannin inhibitors.

**pH-phosphate treatment** involves simultaneous control of both the pH and phosphate content of boiler water. Sodium nitrate can be fed continuously to boiler feedwater or directly to the boiler drum. Its job is to maintain a definite sodium nitrate, sodium hydroxide ratio that inhibits embrittlement. Tannins also establish a definite tannin-sodium hydroxide ratio.

You can often tell the cause of corrosion in steam and condensate systems by corroded part's appearance. Photos above show common types.



**DEZINCIFICATION** of a condenser-tube sheet (90-10 copper-tin) on salt water side. Half of sheet thickness is lost



**PITTING CORROSION** of cast-iron diesel cylinder liner after only six months service. Salt water was cooling medium

**CAVITATION CORROSION** of a bronze impeller in this salt-water circulating pump virtually destroyed impeller blades

# Cooling system corrosion . . . backing up right metal

Cooling-water corrosion might well be one of your major headaches, regardless of whether you're responsible for air-conditioning, steam-power generation, compressed air, refrigeration, diesels, gas engines or heat-exchange processes.

A variety of factors influence cooling-water corrosion. We've listed the most common ones in the table below. Most important among these are water composition—dissolved oxygen and carbon dioxide, pH and dissolved solids. Temperature, velocity, contact with dissimilar metals (galvanic action) also shape up as key factors in many systems.

**Right approach** to the problem depends largely on which type of system you have. You can, for example, economically justify more extensive treatment in recirculating systems than in once-through types, largely because of relative water quantities involved. In open systems, effect of toxic inhibitors in windage and spray losses can be dangerous.

Corrosion control in any of these systems starts in the design stage—good mechanical design and choosing the right metals. Many of today's copper-base and aluminum-base alloys ward off corrosion in heat exchangers and condensers.

From an operations and maintenance viewpoint, corrosion control boils down to chemical treatment, cathodic protection and protective coatings.

**In once-through systems** you can get protection by building up a film of calcium-carbonate scale. Common chemicals for this purpose are soda ash, caustic soda and lime (calcium hydroxide). Lime is usually the lowest-cost method because it raises the calcium content as well as alkalinity and pH, thus creating right conditions for scale buildup. Major drawback to this technique where heat transfer is involved: Difficulty in controlling scale thickness so that you get overall protection without materially interfering with heat transfer.

**Removing dissolved oxygen** itself, attacks the problem more directly. Mechanical deaerating methods like vacuum deaeration do a good job. But relatively high investment and operating costs limit its use.

**Chemical deaeration** with sodium sulfite works well at higher temperatures. But at common cooling-water temperatures the reaction between sulfite and oxygen is slow. Recent development of catalysts to speed the reaction now make chemical deaeration practical.

**Corrosion inhibitors** most widely employed in industrial cooling-water systems are the chromates, polyphosphates, silicates, nitrites and dianodic combinations of phosphates and chromates (a combination of two anodic inhibitors that

## Factors controlling corrosion . . .

### Impingement corrosion

Alloy composition
Water composition
Velocity of water
Sand, marine organisms, gases
Partial obstructions in tubes
Galvanic
Temperature
Vibration
Design, depth of water boxes, radius of bends, etc.

### Pitting

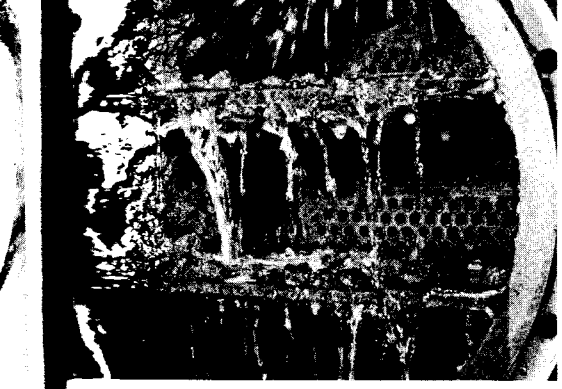
Alloy composition
Water composition
Lack of cleaning (deposits)
Temperature
Sand, silt, muck, marine organisms (deposits)
Surface films
Galvanic
Velocity of water
Vibration

### Cracking

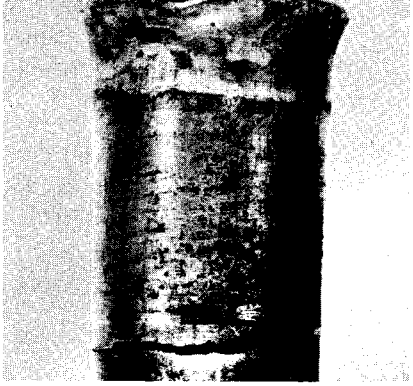
Alloy composition
Creep, temperature
Corrosion fissuring
Stress (residual, static, thermal)
Vibration-fatigue
Corrosion fatigue
Shock
Design
Internal flaws
Slimes

### Thinning or general corrosion

Alloy composition
Water composition
Velocity
Sand, silt, muck, marine organisms
Temperature



SLIME TEAMED UP with calcium carbonate scale and corrosion products in this aftercooler waterbox to clog system



CORROSION FATIGUE crack in a vibrating aluminum-brass condenser tube. Engine vibrations supplied fatigue effect

IMPINGEMENT CORROSION of admiralty condenser tube is due to entrained air (oxygen) in water, destroying film

# with chemical treatment satisfies most needs

produce better results than either used alone). Also showing strong promise are many of the organic inhibitors.

As you might expect, biggest problem with the once-through systems is cost. For this reason, corrosion inhibitors are fed only in sufficient quantity to control severe corrosion. It's the rare once-through system that uses sufficient inhibitor to completely stifle corrosive attack.

**Open-recirculating-system** corrosion can be even more difficult to cope with than corrosion headaches in once-through systems. Intimate contact of the cooling water with air as it passes over the cooling tower or through spray ponds, continuously saturates it with dissolved oxygen. Towers in industrial areas may also be contaminated with sulfur dioxide, ammonia, hydrogen sulfide. And the buildup of dissolved solids—chlorides, sulfates, etc.—as the system cycles, adds to corrosion.

**Closed systems.** For ease of corrosion control, closed systems hold a big edge over other types. Cycling doesn't tend to concentrate dissolved solids. Water doesn't continuously contact the oxygen-laden atmosphere. And system is generally free of "open-system" headaches.

Closed systems make economical use of inhibitors because they lose relatively little water. Thus, chromates are used extensively. But chromates aren't compatible with ethylene glycol anti-freeze solutions. These solutions normally incorporate organic inhibitors.

Closed cooling-water systems almost always get the nod for diesel and natural-gas-engine cooling, and for chilled-water air-conditioning systems.

**Cathodic protection** is a strong contender for guarding once-through systems that face highly concentrated corrosion problems. Where sea water or brackish water passes through condenser circulating-water systems that include steel or cast-iron water boxes and copper alloy tubes and tube sheets, powerful galvanic corrosion cells are likely to exist. Result: Deep pitting of steel water boxes and graphitic corrosion of cast-iron water boxes. A well-designed cathodic protection system can choke off these effects. Protective anodes — often zinc, magnesium or aluminum — are mounted in the water box or on the water-box cover.

**Synthetic-resin-base coatings** we talked about, pp 86-87, can stand up underwater for long periods of time. Thus, they're used to back up cathodic protection by covering water-box sides and cover as well as tube sheets and tube ends. These protective barriers reduce the required number of anodes as well as stretch anode life substantially.

## . . . in cooling-water systems

### Intergranular

Alloy composition
Water composition
Low velocity
Temperature
Stress
Design
Scale or slime

### Dezincification

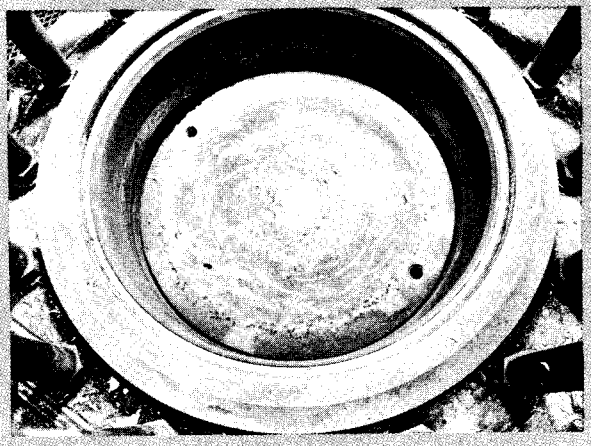
Alloy composition
Water composition
Temperature
Low velocity
Salt, sand, etc.

## Corrosion in refrigeration systems

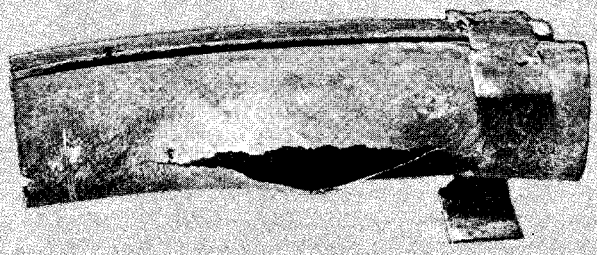
Brines are generally conceded to be chief offenders when it comes to refrigerating-system corrosion. They're strong solutions of calcium or sodium chloride. Because of its low freezing point, calcium brine gets the nod most often.

Corrosion rate depends on type of brine, extent of magnesium-chloride contamination, pH, contacting metals and brine density.

Corrosion committee of the American Society of Refrigeration Engineers makes these recommendations: (1) For calcium brines — 100 pounds sodium dichromate per 1000 cu ft of brine. Also, enough sodium hydroxide (caustic soda) to convert dichromate to neutral chromate. (2) For sodium brines — 200 pounds of sodium dichromate per 1000 cu ft. Add caustic soda here too. And for best results renew dichromate semi-annually.

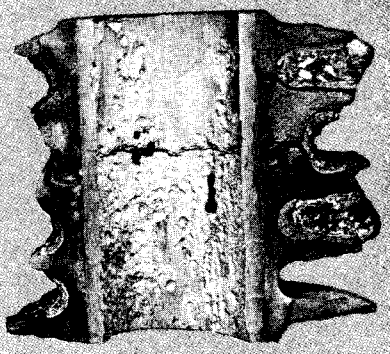


**METAL WASTAGE** on this diesel-engine piston head resulted from harmful impurities in residual fuel oil

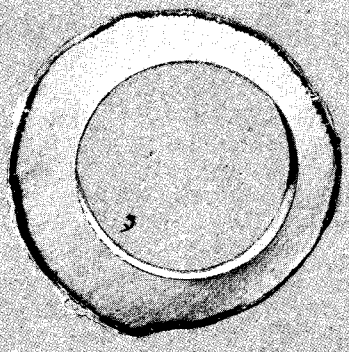


**CREVICE CORROSION** resulted from collection of flyash in annular space between boiler tube and protective pad

**VANADIUM ATTACK,** from vanadium in fuel oil, corroded this superheater hanger. Overheating also contributed



**STRESS CORROSION** of finned economizer tube due to local bending stress



**HIGH-TEMP OXIDATION** resulted from overheating this superheater tube. Abrupt change in scale thickness is spalling

# Combustion... it presents *low-* as well as

We've already seen how temperature affects corrosion, p 91. What happens if we allow temperatures to soar well over 1000 F and compound the problem with the corrosive effects of combustion gases and their condensation products? What steps can we take to avert possible consequences?

Best approach to controlling-combustion-products corrosion is the two-pronged attack stressed throughout this report: Improving metal's resistance to corrosion and taming the corrodent.

**High-temperature oxidation** corrosion generally makes its presence felt by alternate scaling, spalling of oxide layers; *see sketches, facing page.* But if conditions are right for scale buildup, corrosion drops off rapidly as scale thickness grows. Also, oxidation increases as temperature climbs. And rate of increase is greater at higher temperatures.

High-temperature oxidation can occur in pure air or oxygen. But from a practical viewpoint we need to look at it along with a variety of factors that tend to complicate the picture. The presence of moisture or carbon dioxide speeds oxidation. And the effect is more pronounced at higher temperatures. Sulfur dioxide, common component of furnace gas, boosts scaling rate and can bring on deep intergranular corrosion. But, surprisingly, excess free oxygen in the furnace atmosphere tends to nullify the intergranular effect on steels.

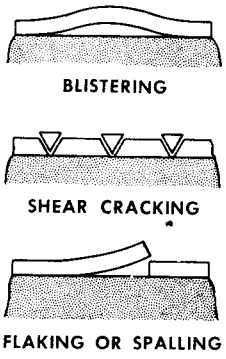
**Velocity** too plays a key role in determining nature of the scale. Scaling, spalling become more intense at higher gas speeds. But *rate* of increase dips and eventually levels off as velocity climbs.

We've already seen how changing the gas atmosphere (supplying excess oxygen) can reduce high-temperature corrosion. Another technique along similar lines: Increasing ratio of carbon monoxide to carbon dioxide in combustion gas. Drawback of this method: It cuts into combustion efficiency. Better way is to boost metal's corrosion resistance.

Boiler, internal-combustion engine and gas-turbine manufacturers are well aware of problems associated with combustion-products corrosion. And part of their first line of defense are today's corrosion-resistant metals. Adding alloying elements—chromium, nickel, silicon, aluminum—to steel, see pp 82-83, goes a long way toward heading off the corrosion problem before it has a chance to start. Widely used ferrous alloys that resist high-temperature oxidation are the high-chromium irons, chrome-nickel irons and austenitic chrome-nickel steels. Superheater steels contain varying amounts of chromium, molybdenum.

**Sulfur, vanadium, alkali ash** and sodium in fuels can be a major headache because they form a low-melting

### How oxide scales break down



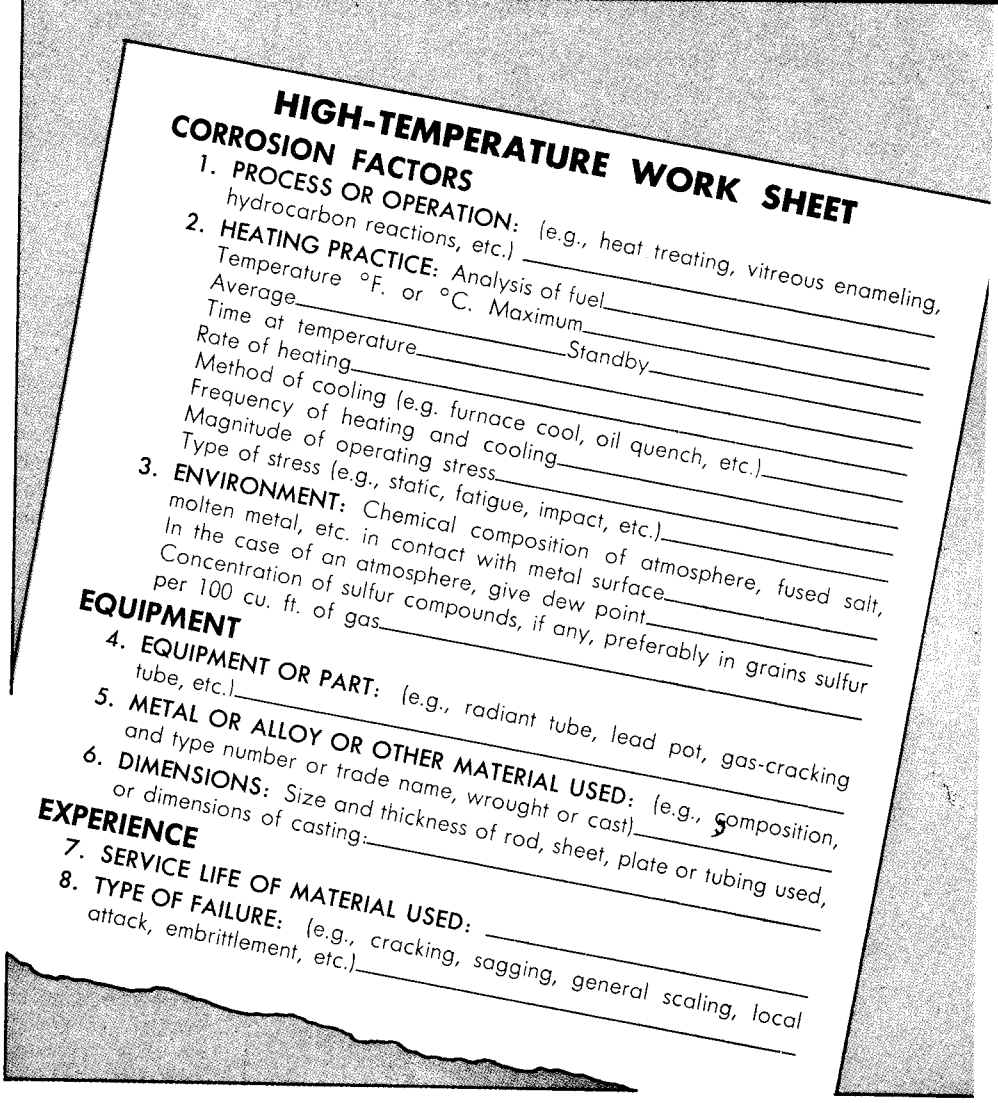

Among factors influencing resistance to high-temperature oxidation, physical characteristics of scale share top importance.

**Blistering** may occur in oxide layers having good elasticity but poor adherence to the metal surface.

**Shear cracking** on the other hand will be found in oxides that are adherent but brittle.

**Flaking or spalling** results when the oxide is both brittle and non-adherent.

As the scale peels away it exposes a fresh area to further attack. And loss of the oxide causes progressive thinning, ultimate failure of the metal.



**HIGH-TEMPERATURE WORK SHEET**

**CORROSION FACTORS**

1. **PROCESS OR OPERATION:** (e.g., heat treating, vitreous enameling, hydrocarbon reactions, etc.)
2. **HEATING PRACTICE:** Analysis of fuel
   Temperature °F. or °C. Maximum
   Average Standby
   Time at temperature
   Rate of heating
   Method of cooling (e.g. furnace cool, oil quench, etc.)
   Frequency of heating and cooling
   Magnitude of operating stress
   Type of stress (e.g., static, fatigue, impact, etc.)
3. **ENVIRONMENT:** Chemical composition of atmosphere, fused salt, molten metal, etc. in contact with metal surface
   In the case of an atmosphere, give dew point
   Concentration of sulfur compounds, if any, preferably in grains sulfur per 100 cu. ft. of gas

**EQUIPMENT**

4. **EQUIPMENT OR PART:** (e.g., radiant tube, lead pot, gas-cracking tube, etc.)
5. **METAL OR ALLOY OR OTHER MATERIAL USED:** (e.g., composition, and type number or trade name, wrought or cast)
6. **DIMENSIONS:** Size and thickness of rod, sheet, plate or tubing used, or dimensions of casting:

**EXPERIENCE**

7. **SERVICE LIFE OF MATERIAL USED:**
8. **TYPE OF FAILURE:** (e.g., cracking, sagging, general scaling, local attack, embrittlement, etc.)

**SIMPLIFIED FORM—high-temperature work sheet—is filled out and returned to corrosion-resistant-metals producer who supplies data, helps you choose right metal**

# *high*-temperature corrosion problems

slag which is extremely corrosive metals and alloys above 1200 F. Treating Bunker C oil, for instance, remove one or more of these impurities or using additives to raise the melting point are possible cures.

**esels.** If cylinder-wall temperatures are above the dew point, sulfuric acid doesn't form (from combustion products of sulfur-bearing fuels). But there's little likelihood of corrosion. But light-load operation drops temperature, makes sulfuric acid formation easier. And ash content of the fuel as well as poor combustion conditions can, if you allow them to go unchecked, contribute heavily to corrosion.

**boiler** is afflicted with high-temperature oxidation it generally will crop on external surfaces of tubes exposed to radiant heat. Metal surface is rough and looks flat.

**ower temperature sections**—air heaters, economizers, stacks—of boiler combustion-gas systems, requirement of low flue-gas temperature for high boiler efficiencies comes in conflict with the corrosion problem. When a high-vanadium fuel burns at temperature that melts the ash combustion products, vanadium ash deposits as a corrosive dense-slag residue. Also, vanadium acting as a catalyst promotes formation of sulfur trioxide from sulfur dioxide. Result: Corrosive sulfuric acid when combustion gases dip below their dew-point temperature.

Today's boiler designers lick the problem via several routes. They determine and stay within minimum allowable tube-metal temperatures in designing air heaters, economizers. In pinning down these temperatures they take into account type of fuel burned, firing method.

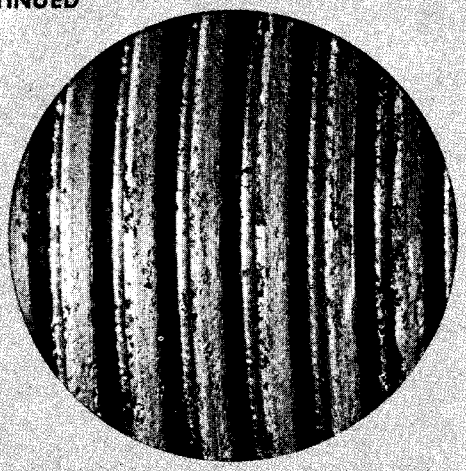
**Corrosion-resistant steels** are often teamed up with flue, duct and stack linings made of corrosion-resistant concretes and refractories. Also, glass-lined stacks, p 89, are beginning to enter the picture.

**Advent of fuel additives** in recent years to retard combustion corrosion has produced some good results. But you'll do well to exercise extreme care in their use. An additive that does a good job under one set of conditions may be completely ineffective under conditions that *seem* to vary only slightly. Where sulfur acids cause trouble, additives are generally alkaline compounds. Aluminum and silicon compounds are often favored to cope with sodium, vanadium in fuel.

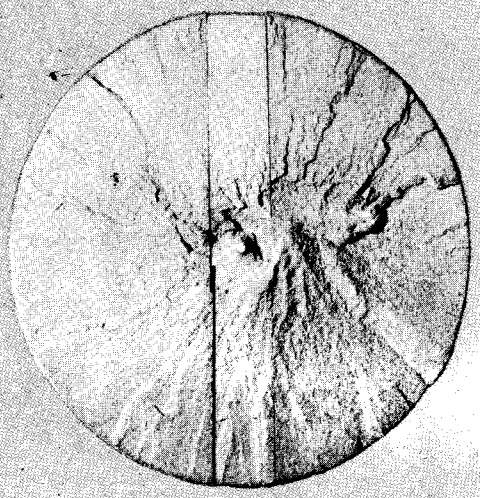
When firing vanadium-bearing fuels it's possible to get a soft ash that's more readily removable and less corrosive than hard slag deposits that can form in superheater regions. Additives of aluminum, calcium and magnesium oxides yield these results.

Some additives — kaolin, dolomite, magnesia — are injected directly into combustion chambers.

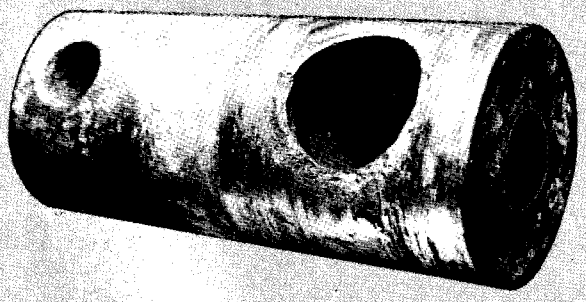
CONTINUED



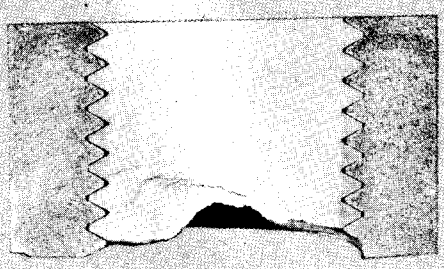
**STUD BOLT from turbine casing failed due to stress-corrosion cracking. Cracks reduced effective bolt area**



**PUMP SHAFT lost about 3/8-in. diameter due to uniform corrosion. Then fatigue cracks promoted fracture**



**PLUG from 1-in. plug valve shows affects of impingement corrosion attack along edge of the plug's opening**



**BOLT from turbine's dummy cylinder was tightened too much, causing high stress that teamed with corrosion**

# Machinery, structures . . .

Not too many years have passed since accepted practice was simply to beef up machine and structural parts enough so that even with severe corrosion there was little possibility of failure. We recognize such practice today as an approach that sidesteps the *real* problem. Present thinking is to *corrosion-engineer* machinery and structures as an integral part of good mechanical design.

**Most common corrodent** of above-ground structures is the atmosphere. Its effects vary with the seasons, geographical areas, extent of air pollution. But entrained moisture in the atmosphere overrides all other factors. Sulfur dioxide, hydrogen sulfide and other contaminants corrode metal much faster in moist air than in dry.

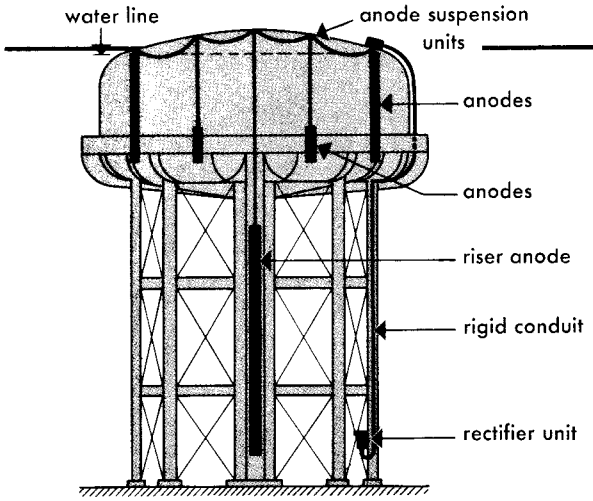
**Chemicals** used in industrial processes attack machine and structural members. But metallurgists have come up with metals that are formulated to handle even highly corrosive chemicals, pp 82-83. And many effective barriers are tailored to withstand chemical attack, pp 86-89.

**Stress.** Experts differ on whether static and dynamic stresses *cause* corrosion. Some findings show no cause-effect relation. Others show that stress accelerates corrosion. Some even report an inhibiting effect. But, clearly, where both stress and corrosion are present, action is a snowballing one that can lead to cracking, ultimate failure of vital machinery and equipment.

**Operating temperatures** have special importance where you're dealing with corrosion of moving parts. Even small jump in temperature can initiate corrosion in an otherwise smooth-running bearing.

Having pinpointed the possible bad actors we turn our attention to ways of thwarting them. The familiar standbys —metals, inert barriers—are once again our first line of defense. On a tonnage basis, the low-carbon structural steels—not especially conspicuous for their corrosion resistance—are most important. Thus they're almost always teamed with protective coatings, mastics or linings.

In protecting outdoor steel structures with paints, periodic maintenance, inspection and renewal of coatings can stretch




**CATHODIC PROTECTION of elevated water storage tank guards tank's inside walls. System anodes are shown oversize**

# . . . corrosion-engineer them in the blueprint stage

their life span many years. How frequently you renew coatings depends on severity of the atmosphere.

**Cathodic protection** for the insides of such structures as elevated water-storage tanks, water-treatment tanks, chemical-process vessels, can be economically attractive. But you'll need to check required current density, probable anode life, number of anodes. Size of the installation and solution's tendency to corrode the tank are controlling factors. Unless you're thoroughly familiar with cathodic-protection system design, it'll pay to call in a company specializing in such installations. Sketch, *bottom of facing page*, shows how an electrolytic cathodic protection system is hooked up to protect the inside of a large elevated water-storage tank. Rectifier supplies dc power.

**Bearings**—because they're load carrying elements and contacting surfaces—are potential weak spots in the anti-corrosion armor of any machine. Bearing metals, operating conditions and lubricants rate a long, hard look before you specify them for your service systems.

**Stability of lube oil** plays a key role in bearing corrosion. Here's why: If oil doesn't break down, its film-forming ability makes it an excellent corrosion preventive. But if it readily oxidizes (becomes unstable), oxidation products may attack bearing metal. Solvent-extracted paraffinic oils have much stronger corrosion tendencies than the napthenic types. But virtually all of today's lubes give good anti-corrosion performance by blending them with additives.

**Stabilizing additives**—phosphorous, sulfur, phenolic and aromatic-amine base types—in small concentrations keep oil from breaking down under most bearing service conditions you're likely to encounter.

**Bearing metals** vary considerably in their corrosion resistance. Older tin-base babbitt bearings are less affected by lube-oil oxidation products than cadmium-base and copper-lead bearings. But copper, cadmium types have greater high-temperature strength. Also, economics often favor the copper base. Lead-indium and lead-tin coatings applied to copper-lead bearings boost their corrosion resistance.

**Equipment design.** Earlier we said that corrosion-engineering is a part of good mechanical design. Here, in brief, are some of the more common ways to lick machinery and structure corrosion in the *blueprint* stage:

(1) Avoid sharp corners where possible. They act as stress raisers and are likely spots for stress-corrosion cracking. Sharp corners also cause thin spots in protective coatings and linings.

(2) Joining hardware – rivets, bolts, screws – are vulnerable to crevice corrosion. They tend to form concentration cells by starving metal areas of oxygen, page 78. Where you must use them, consider advantages of hardware made from the same metal as parts being joined. You'll steer clear of possible galvanic couples.

(3) Where statically stressed members operate in corrosive atmospheres be sure corrosion can't reduce load-carrying areas to unsafe levels.

(4) Give special attention to vibration conditions where heavily loaded parts such as bearings are press-fit. If such parts slip (due to vibration), fatigue cracks may start. Result: Fretting corrosion, see page 79.

(5) If you can't avoid teaming two metals that may form a galvanic couple, design the anode so that it's large compared to the cathode.

(6) Study the effects of cyclic stresses. Part may be within safe stress limits at first. But corrosion may team up with fatigue effect of stress reversals, bring on eventual failure.

**Maintenance cleaning** of parts can thwart pitting attack. When corrosion products form over new pits they speed the attack. But if you remove corroded material before pit gets too deep, corrosion is likely to shift to another area. By keeping corrosion uniform over an entire metal area its pitting effect can be materially reduced.

## For coal-handling structures:

Coal has three characteristics that make it uncommonly gifted in corroding and eroding its handling equipment: First, sulfur reacting with ever-present moisture forms a weak solution of sulfuric acid. Second, coal is abrasive. As it flows over a rough, corroded surface, wear is intensified. Third, moisture-laden coal fines have a tendency to pack, especially under lot-storage conditions.

One relatively low-cost answer to the problem—stainless-clad steel—has come in for a good bit of attention recently. Here's one case history: At a large eastern utility, carbon-steel chutes had a life expectancy of roughly four years. Corrosion on inside surfaces was responsible for many coal-flow stoppages. The company investigated and installed a stainless-clad hopper and chute. After 9½ years there was no loss of cladding. Only effect of the coal was to polish the clad surface to a shiny finish.

## This is corrosion fatigue!

**Pinion gear, subject to cyclic loading, initially operated at safe stress levels. But small corrosion pits soon developed as a result of moisture entrained in the lubricant. Pits acted as stress raisers. When local stresses exceeded failure stress of the metal (a chrome-nickel-moly steel), cracking started. At first, crack grew under the impetus of moisture in the lube oil. Later, fatigue took over.**

**Possible cures: Check lube for moisture, other contaminants. Consider altering metal composition.**

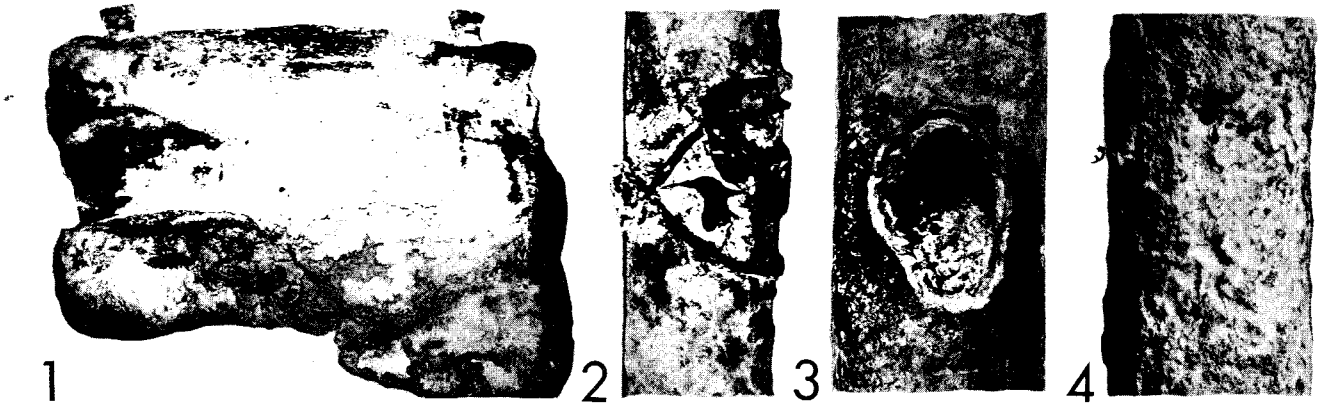
# Underground corrosion . . . soils and stray currents

You'd be hard pressed to find any of today's industrial plants without one or more of their key services—electric power, fuel oil, steam, condensate returns, water supply, air, water piping—flowing underground. The cable, piping, tanks and other structures that make up these services can be attacked by many of the familiar corrosion culprits we've talked about thus far. And—making underground corrosion even more complex than corrosion above ground—several new ones enter the picture. Here, in brief, are key items:

**By far the most important**—from the plant and corrosion engineer's viewpoint—is condition of the soil. It can be corrosive or it can be relatively noncorrosive, depending on a variety of chemical and physical characteristics.

**Symptoms of noncorrosive soil** are: high pH, low moisture content, sandy structure, little organic matter, light color, high oxygen content, low temperature. In contrast, corrosive soils are generally acid, contain substantial amounts of moisture, clay and organic material, appear

## Where your underground systems are vulnerable




**1: LEAD CABLE SLEEVE corroded due to free lime in underground concrete. The corrosion product is a lead oxide**
**2: GALVANIC ACTION at the brass phase tag of this lead-sheathed cable caused corrosion. Insulation tape solved the problem**
**3: BURIED CAST-IRON water main corroded due to action between cast iron, cinder fill. PD can go has high as 1 volt**
**4: BURIED LEAD water pipe suffered stray-current corrosion from stray railway currents. Drainage solves problem**

## What you can do about it

In talking about soils, *top of page,* we said that high resistivity is one mark of a noncorrosive soil. Yet, when it comes to cathodic protection of underground power services we generally try to look for a low-resistivity (1000 ohms per cc or less) soil in which to bury our anode systems (ground beds). Here's the reason: Successful cathodic protection depends on *encouraging* current flow from anode to cathode. And soil is the major factor in circuit resistance. In electrolytic cathodic protection systems, low soil resistance means low power input. In galvanic systems, low soil resistance means more protective current from a given set of anodes.

**Choosing a site** for ground beds often boils down to comparing differences in power cost or quantity of protective current with differences in installation cost. Thus, you may find a low-resistance soil. But its location (accessibility, distance from plant, etc.) could nullify potential-power and protective-current savings.

**A careful economic study** will also help you decide between electrolytic (rectifier-type) and galvanic protection. We've seen, page 81, that rectifier protection fits where you need large blocks of current at few locations. Also, ac power must be easy to get. Galvanic types do best where current requirements are low, soil resistivity is low and ac power is hard to come by. But remember: These are only general rules of thumb. You'll have to weigh each situation on its own merits.

**The field survey** is an important initial step, before committing yourself to a specific cathodic protection system. Most important: You'll need data on soil conditions—moisture, pH, resistivity, density, etc. Buried structure-to-soil potentials are an excellent indication of the protection you need *and* of the effectiveness of your protection system *after* it's installed. Good anti-corrosion practice for buried coated pipe calls for keeping the pipe close to 0.85 volts negative to the ground (when using a copper-copper sulfate ground-reference electrode).

If you have abandoned structures close to equipment you want to protect, they can make an economical ground bed. Many power companies cut protection costs for buried power cables by using scrap rail or pipe buried in the earth, next to the cable duct bank. They apply a positive potential (via a rectifier hookup) to scrap-material anodes and impress a current flow through the earth to the power cables.

# are added headaches

dark, hold little oxygen and are relatively warm to the touch.

No one of these earmarks, by itself, establishes the soil as corrosive or noncorrosive. It's the combined effect that counts. And—as you might expect after looking over these symptoms—a soil can become more or less corrosive with seasonal weather changes.

You can get a good indication of what a soil will do to buried metal by measuring soil's electrical resistivity. High-resistivity soils cut down corrosion currents.

### The soil survey is important—*but*

In the present state of the corrosion-combatting art, researchers have yet to devise a single overall index of soil corrosivity. Often, the same soil will have traits that put it in both corrosive and noncorrosive classes.

Tests run by the National Bureau of Standards, attempting to correlate soil corrosivity with other soil properties, showed that noncorrosive soils have high resistivities (several thousand ohms per cc). But they also found that noncorrosive soils could have high or low aeration and high or low acidity. Thus, while soil studies are important, it's even more important to weigh *all* data you get from them. And be sure to double check the validity of such studies by corrosion tests at regular intervals *after* equipment is installed.

What can corrosion do to your underground services? Where is your underground system most vulnerable? You get a not-very-pretty answer to the first question by a glance at the photos, left. Here are some likely answers to the second:

**Electric cable sheath.** Poor soils aren't the only reason why underground cable sheath corrodes. Nearby metal structures can be cathodic to lead cable sheaths, cause stray corrosion currents to flow. Fortunately, lead sheath is close (in the galvanic series) to steel and iron pipes. But, if conditions are right, you can set up a strong galvanic couple. In the past, street railways were a principal source of stray current largely because of their relatively low rail-to-earth resistance.

**Copper-clad ground rods** and copper grounding cables have been the cause of many a lead-covered-cable failure at generating and substations. With lead sheaths solidly interconnected to bare copper, lead will corrode, fail—especially if soil and cable duct resistance are low. One practical solution: Jacketed cable.

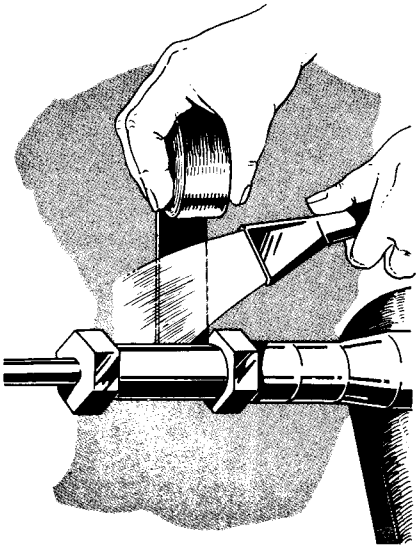
**Your plant's grounding** system itself can be knocked out by corrosion if you don't provide it with adequate protection. Steel grounding rods and connecting grounding buses may be anodic to nearby buried structures. Or, differences in soil pressure, stretches of wet soil followed by dry soil, scratches, breaks and abrasion of grounding components may combine to set up local corrosion cells between different areas *within* your grounding system.

**Buried piping** is subject to much the same corrosion conditions as sheathed cable. When we bury pipe, we set up many local anode and cathode areas on it. Here's why: (1) Different sections of the pipe may be contacting soils of different chemical, physical traits. (2) Newly buried pipe is generally anodic to old pipe connected to it. (3) Soil aeration may be different at various points in contact with the pipe.

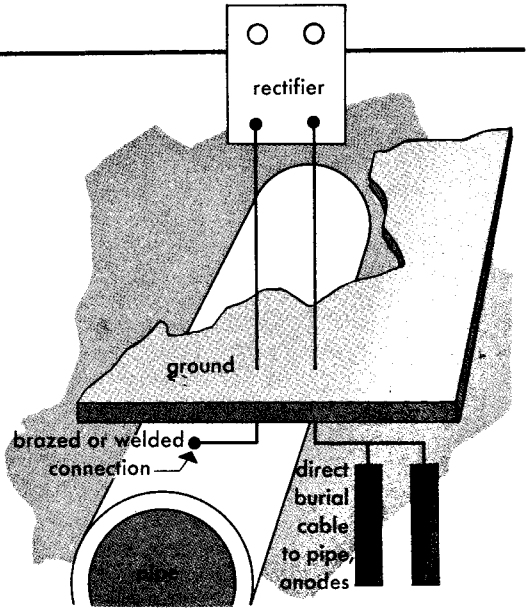
Galvanic cells due to nearby structures also cause buried pipe to corrode.

**Electrolysis drainage** (electrolysis refers to action of current on the anode) is a practical, low-cost way to tame stray-current corrosion. These currents can come from electric railway systems having rails poorly insulated from the earth, electric welding units, cathodic protection systems, electroplating plants, etc. The buried metallic structure that corrodes acts as a low-resistance path and tends to collect these stray currents. The drainage system simply makes an electrical connection between the buried metal (cable sheath for instance) and the negative feeder of the source of stray current.

**Protective coating and jacketing,** pp 86-87, are often the first line of defense for underground piping, cables. These inert barriers are lower cost and generally easier to justify economically on smaller buried structures.



**RESIST CORROSIVE SOILS** by coating and wrapping underground pipe-systems with hot-applied coatings and asbestos felt




**RECTIFIER-TYPE** cathodic protection for underground pipes, cables, fits if you need large currents at a few points

# CORROSION TESTS... they supply vital data for your important corrosion-control decisions

Behind every successful corrosion-control program you'll find a solid foundation of reliable information. The info-gathering operation begins in the early program planning stages and never actually ends. Even after corrosion-control efforts have become relatively routine, keeping close tabs on their effectiveness pays off.

Broadly speaking, corrosion testing divides into (1) lab tests and (2) in-plant and field tests. Here we concern ourselves mainly with the latter because plant and power-service men find greater occasion for actually running such tests. But it's important to recognize that lab testing facilities are available to even small companies. Corrosion-resistant materials producers and corrosion consultants, are staffed with specialists that run lab tests on corrosion samples which are sent in after being exposed to plant and field conditions. Also, the results of lab tests run by such organizations as The National Bureau of Standards and by members of The National Association of Corrosion Engineers are available in handbooks, engineering society technical papers, etc. Such data are an important source of practical information for engineers concerned with corrosion control and related problems.

**Plant and field tests** generally break down into direct observation, mechanical, chemical and electrochemical, and electrical. Chances are, you won't be running all of them in your plant. Soil corrosion, for instance, is mainly checked by electrical, chemical tests. Water corrosion data stems largely from chemical tests. Atmospheric corrosion—especially where protective coatings are used—is often a matter of visual inspection or photographic methods.

## Direct observation is simple, fast, but has several drawbacks

The chief advantage of direct-observation tests are their simplicity. But, unless you supplement them with more exact techniques, they have some serious drawbacks. You can't use them until *after* equipment that's likely to corrode is actually installed. And used alone, they can be *too little* and *too late*. *Accidental* direct observation is too often the only form of corrosion control in operation. Yet, once you recognize the limitations of these visual tests they can become a valuable asset to your corrosion-control program.

If you're responsible for visual tests, be sure plant men can write brief but accurate descriptions of corrosion conditions they see. It's important, for instance that "severe corrosion" means the same thing to everyone responsible for visual checks. Class-room writing sessions with operating men are a big help in boosting test efficiency.

**Photography** is a first-class tool for showing the progress of corrosion—or lack of it. Often, color photos help you spot different types of corrosion product at a glance.

**Another visual technique** that's sometimes helpful but not always easy to run: plaster casts of corroded parts.

Continual direct observation is of key importance wherever you've applied inert barriers. By alerting plant operators (who aren't necessarily responsible for corrosion problems) to watch for breaks in coatings, mastics, linings on equipment they operate, you'll get better results from inert barrier protection—and at no extra cost.

## Mechanical tests keep close tabs on corrosion rate

Mechanical tests, as we view them here, include (1) dimensional measurements. For example, measuring depth of corrosion pits. (2) Gain-in-weight tests. They're useful where it's easy to weigh the metal plus its corrosion product. (3) Loss-in-weight tests—where corrosion products break loose and are easy to remove.

**The micrometer pit gage** yields valuable info on the extent of pitting corrosion. By measuring extent of pitting at regular time intervals you can plot a time-depth curve that can be an excellent guide for estimating corrosion rates, expected life of equipment. Important: Don't forget to keep an accurate record of the location of each pit you're "tracking." And be sure to take into account the distribution of pitting in interpreting your results.

**Electrical instruments** that read directly in micro-inches of corrosion consist essentially of a metal test element exposed to corrosive conditions. The element is part of an electric circuit on which change-in-resistance measurements are made as the test element corrodes and reduces in cross-section. (Note: Since the instrument reads directly in mechanical units, we classify it as a mechanical test.)

Earlier, pp 86-87, we said that film thickness is crucial in getting good results from protective coatings. Thus, we need reliable ways of measuring films. Simplest method is micrometer measurement. By gaging several sections of the equipment before and after coatings are applied you can be reasonably sure of staying within protective-coating manufacturer's recommendations.

More complex thickness-measuring devices include needle penetration (an electrical circuit picks up contact with the base metal), change-in-magnetic-force and change-in-inductance measurements.

**Change-in-weight tests**—either gain or loss—are relatively simple, easy to run. But they're subject to a variety of errors: Moisture content of the corrosion product may vary. You may not remove all corrosion product. And test doesn't tell whether the attack is concentrated or evenly distributed over the metal's surface.

Weight tests are generally run on standard metal samples exposed to the corrosive atmosphere. ASTM recommendations are available for test specimens as well as specimen holders. Samples are weighed on an analytical balance.

**Physical properties tests**—tensile strength, etc.—before and after corrosion are also highly useful.

# Chemical and electrochemical tests for the in-plant lab

Chemical testing—especially the complete chemical analysis of corrosion products, soils, waters—is often a lab affair. But resulting data are highly useful.

For steam- and water-system corrosion there are several simple in-plant lab tests that keep tabs on corrosion.

**Common alkalinity test** is based on a titration with sulfuric acid. (Note: Standard acid solutions are often used to measure the concentration of alkaline solutions. The acid is added, drop by drop, to the alkaline solution until the neutral or end point is reached as shown by the color change of an indicator such as phenolphthalein or methyl orange. We call this process titration.)

pH is a measure of the effective rather than the total alkalinity of a solution. Index of pH is a number between 0 and 14. At pH of 7, solution is neutral. pH above 7 is increasingly alkaline. pH below 7 is increasingly acid.

**The colorometric test for pH** depends on the color reactions of different chemical indicators. Each indicator in a test set covers a different pH range.

**The electrometric pH meter** measures voltage across two electrodes in contact with the solution. Voltage of one electrode is fixed. Second electrode's voltage varies with solution pH. The pH meter is usually faster than color tests.

**Free mineral acidity** is due to strong acids—sulfuric, nitric and hydrochloric—in water.

You can test for free mineral acidity by titrating sample water with a standard sodium carbonate solution in the presence of methyl orange indicator.

**Test for free carbon dioxide** is by titration of the sample water with a standard sodium carbonate solution in the presence of phenolphthalein.

**Test for dissolved oxygen** by the Winkler method also involves titration. Oxygen in water reacts with manganous hydroxide to form manganese hydroxide. Following a reaction with sulfuric acid, solution releases free iodine in proportion to the amount of oxygen absorbed. Free iodine is then titrated in the presence of a starch indicator. The disappearance of blue color signals the end point.

# Electrical tests for voltage, current, resistivity

**For potential measurements** be sure the internal resistance of the instrument you use is very high compared to resistance of leads, electrodes, and resistance to earth of reference electrodes.

Briefly, common potential measurements and instruments that fit are: (1) Rectifier potentials. Where you're installing impressed-current cathodic protection, any voltmeter with required range will work. (2) Structure-to-structure potentials. Often, buried structures are big and have low resistance. Thus, either a low- or high-resistance millivoltmeter or potentiometer does the job. The potentiometer, *right,* features a calibrated dial with a standard cell for calibration. (3) Structure-to-earth potentials. Either galvanic potentials or potentials due to stray currents can be handled with a high-resistance voltmeter. (4) Open-circuit structure-to-anode potential. Either low- or high-resistance voltmeters are usually OK. But if the structure is well-coated pipe or cable with a high resistance to earth, the high-resistance (50,000 to 500,000 ohms per volt) meter is your best bet. (5) Voltage-drop measurements on a structure tell the amount and direction of current flow. Thus, they can show up galvanic corrosion. Generally, low-range millivoltmeters get the nod.

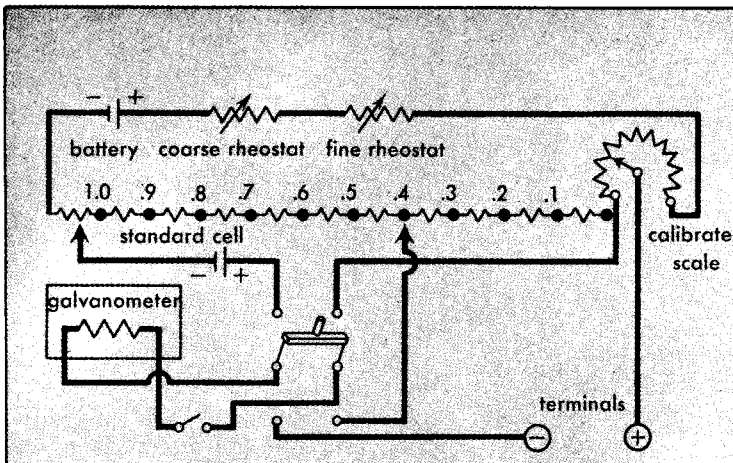
**Current measuring instruments** — milliammeters and ammeters—self-contained or with external shunts, measure the wide range of currents you'll encounter in field testing. If the external circuit resistance is very low, meter's internal resistance may cause substantial error. One practical answer: the zero-resistance-type ammeter.

Common measurements are: rectifier current, electrolysis drainage current, galvanic current between structures.

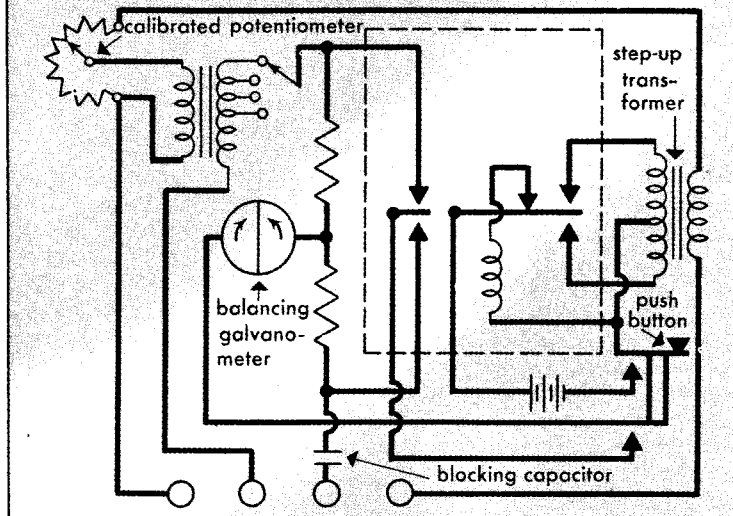
**Resistivity instruments** can tell you, in advance, how much trouble to expect from underground soil corrosion. They measure the resistivity of the undisturbed soil. Or, they can measure a soil sample in the lab.

The 4-terminal method uses two potential and two current terminals, *drawing at left.* Same instrument measures anode and circuit resistance.

Two-terminal instruments, or two terminals combined in a single rod measure soil resistivity to shallower depths.




**POTENTIOMETER with standard cell and calibrated scales can be used for a variety of field potential measurements**




**RESISTIVITY METER has two current, two potential terminals. It measures soil, circuit and anode resistances**

# PLANNING FOR CORROSION CONTROL . . . start

You're plant engineer for the XYZ manufacturing company. Your major responsibilities are the power and plant services. Capital tied up in equipment for these services represent a substantial **part** of the total plant investment. So—facing facts—you try to protect the investment by organizing a corrosion-control program.

To complicate the picture you're saddled with responsibility for controlling corrosion of production equipment.

Where do you start? What likely administrative problems must you handle? How do you make sure you're getting the most for your money? Who can you turn to for assistance? These—and many more—are questions that doubtless will come up.

Before digging for answers that will help to put you on

## Figure your annual bill for corrosion

Finding out your annual bill for corrosion isn't easy, especially if you're just setting up a new plant. But corrosion info on similar plants may be available through the professional societies, consultants, technical publications, etc. In any case it'll pay to check your figures against those of a similar plant.

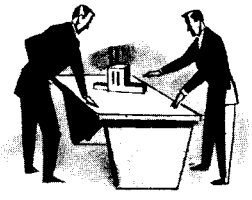
First step: Review maintenance records for all equipment. Find out where down time was due to corrosion. And be sure to include the cost of lost production.

Next, study past plant equipment budgets. Where equipment has been replaced before its expected life span, find out from maintenance, salvage records whether corrosion played a significant role.

Where corrosion is clearly the cause of shortened equipment life, get present-day costs of the equipment and figure out how much premature scrapping of equipment is costing your plant.

The safety hazard that corrosion represents is an intangible cost.

## Sell management on protection economics

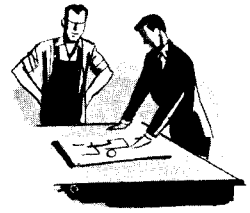


Armed with the facts and figures your next step is to sell management on corrosion control. You should be able to tell them expected savings for every dollar they invest.

Alert management men need to know how much over-all life of equipment will be extended if they OK your proposals. By citing the cost of future replacement, reconditioning, lost production, wasted manhours, chances are you'll come up with impressive potential savings.

Make sure your report is brief, complete. Avoid going into lengthy discussions of fine points, but be prepared to back up your broad economic conclusions with detailed engineering info.

## Talk it over with plant operators



Once you've sold top management on protection economics, chat with plant operating men about your plans. The more they know about what you're trying to accomplish, the more likely are your program's chances for success. What's more they may be able to give you much valuable information, help you avoid pitfalls. And don't forget: In many cases you'll be talking to the men who will actually carry out your program in the plant.

Running informal classroom sessions with plant men on the value of good corrosion control pays big dividends. Some companies even make use of demonstrations showing the corrosion cell in action, measure its corrosion current and potential, page 76. It's a vivid way of making plant operators *corrosion conscious.*

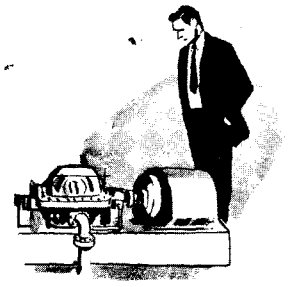
Pointing up the safety hazards of corroding equipment hits home with everyone—management and operating men alike.

## by lining up the facts, selling management and operating men

the right track, first decide whether your plant's corrosion problem requires the services of a full-time corrosion engineer and staff. Or, should you—with the help of outside consultants and advice from equipment suppliers—carry the ball yourself?

Size of plant, nature of its operations, extent of power services are items you and your top management will need to weigh. But regardless of which approach gets the nod, be sure you've taken a close look at all the factors. And remember: The small as well as the big plant can profit by enlisting the help of an outside consultant in making a survey of overall anticorrosion needs.

In the sections below we talk about essentials of a six-point approach to practical corrosion control.



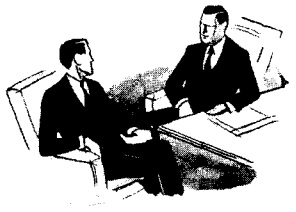
### Take a close look at maintenance practices

One of the important initial steps in getting your corrosion-control program *on the road* is a top-to-bottom review of plant and equipment maintenance practices.

*You* know that different metals in contact can—if conditions are right—lead to galvanic corrosion. But do your maintenance procedures recognize this fact? Do they, for example, call for insulation of cast iron mains from copper services—especially on buried systems?

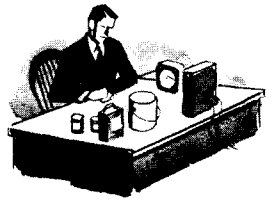
Are your protective coating maintenance programs sound? Do you check to see that coating thickness follows manufacturer's specs? Are you carefully coating steel mains but neglecting cast iron or brass valves connected to these mains? If so, you're not getting full mileage from your coating maintenance program.

By carefully mulling over your maintenance standards you may find many corrosion loopholes such as those we've just cited. Plugging them is often a simple matter. And it pays off handsomely.



### Consider the advantages of consultants

Corrosion engineering, by its nature, is a compilation of specialized and complex areas — metallurgy, electricity, chemistry. It's not likely that the plant engineer or even a single corrosion engineer is thoroughly versed in all of its facets. Thus, a group of consultants can be well worth their fee. Here's how you can use them: (1) In the formative stages of direction, training and guidance of a full time corrosion engineering staff. (2) Where extent of the need doesn't warrant a full-time corrosion specialist. (3) Where specialized highly-technical problems come up that can't be tackled by the in-plant staff. (4) To make overall corrosion surveys.



### Decide on men, records and equipment

Your anti-corrosion program can be no better than the men who run it, the records they keep, the equipment they use.

In choosing a corrosion engineer, remember: He'll be making decisions that will be responsible for spending thousands of dollars. So judgement errors on his part are likely to be costly. Thus, his technical background, personality should be on a par with top-level engineers in your plant.

Corrosion records—or lack of them—can make or break any corrosion-control program. They're needed to make intelligent estimates. They pin down causes of corrosion trouble. And they eliminate committing important info to memory.

Your anti-corrosion arsenal needs good equipment—instruments, inert barrier materials, chemicals, etc. Once your corrosion men get to know all available types they'll be in a position to choose equipment that meets the special needs of your plant.

## Is your company needlessly paying part of industry's multi-billion dollar annual bill for corrosion? Here's a check list to help you find out.

- Do you assign a man (whether his title is Plant Engineer, Power-Service Engineer, Corrosion Engineer, Metallurgist or Maintenance Engineer) to be specifically responsible for corrosion control in your plant?
- Do you know that in many plants maintenance workers (often busy curing corrosion headaches) now outnumber production workers and that this trend is increasing rapidly?
- Are you aware that new materials and techniques can prevent types of corrosion which were previously regarded as inevitable?
- Is your budget for corrosion control in line with today's costs for construction materials, labor and equipment?
- Do you know that it's possible to save several times your Corrosion Engineer's salary by making full use of his services and recommendations?
- Does your design department consult the Corrosion Engineer when it plans new construction projects?
- Does your purchasing department make full use of the Corrosion Engineer's technical know-how when it buys new materials, equipment?
- Are you aware that forward-looking companies—by the application of modern methods of corrosion control—have actually been able to reduce the selling price of their products, thereby gaining a competitive advantage?
- Do you take full advantage of the services offered by corrosion-engineering consultants and manufacturers (metals and inert barrier producers, cathodic protection specialists, etc.)?
- Have you—recently—reviewed the efforts of your company to improve corrosion maintenance practices and to reduce avoidable waste?


### ACKNOWLEDGEMENT

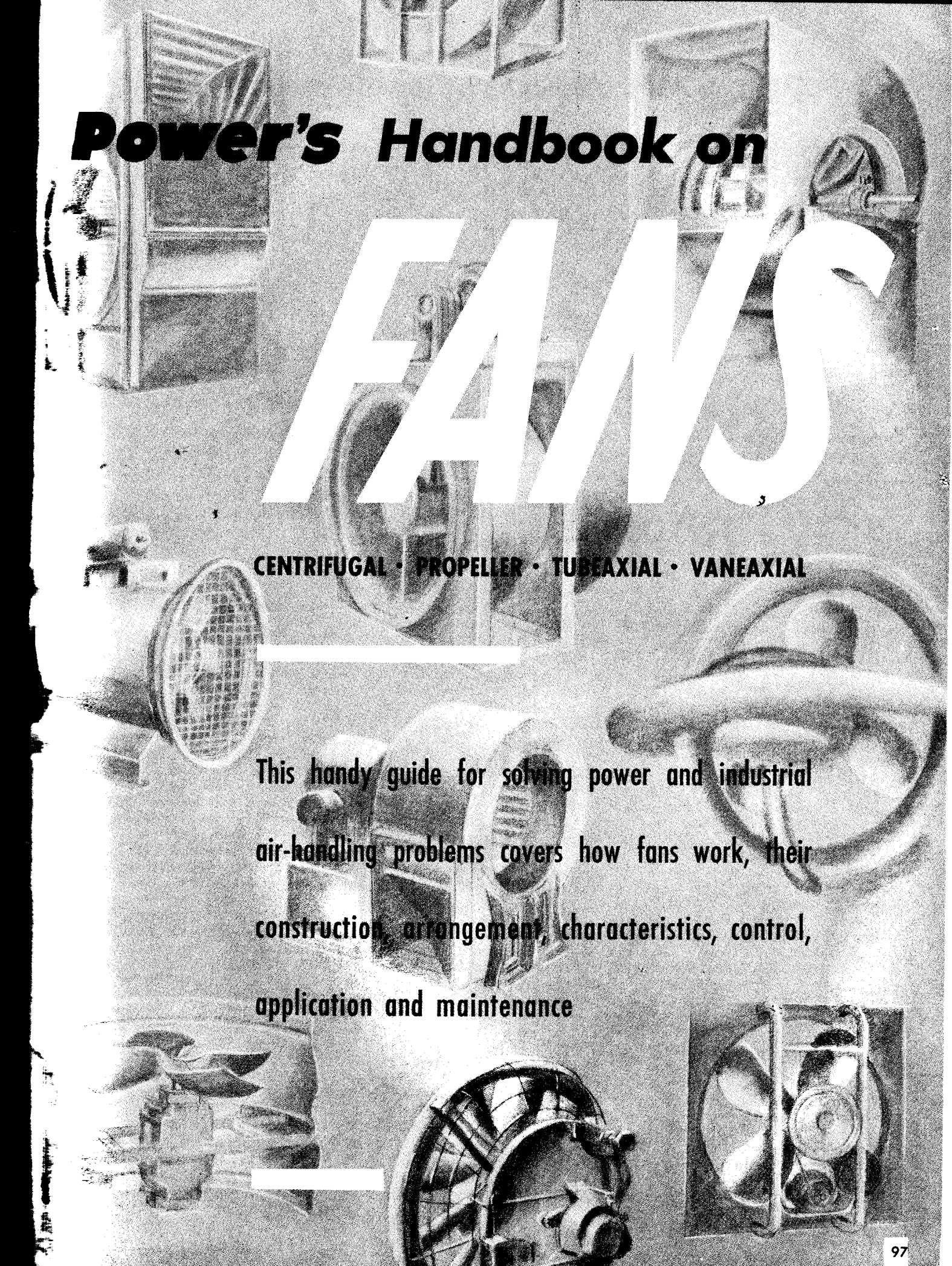
Power is indebted to the many producers of corrosion-combatting materials and equipment, consulting engineers, professional societies and trade associations. They have generously supplied technical data as well as helpful advice and criticism in the preparation of this report.

# Power's Handbook on

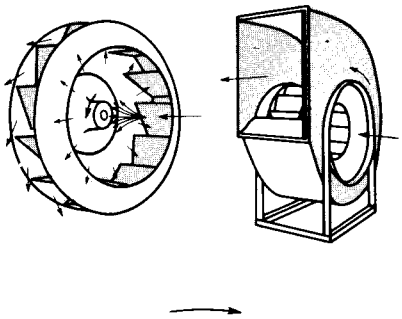
# FANS

**CENTRIFUGAL • PROPELLER • TUBEAXIAL • VANEAXIAL**

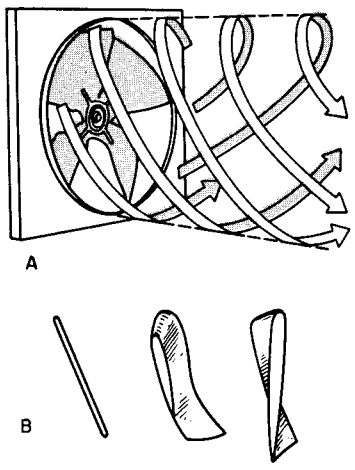
This handy guide for solving power and industrial air-handling problems covers how fans work, their construction, arrangement, characteristics, control, application and maintenance



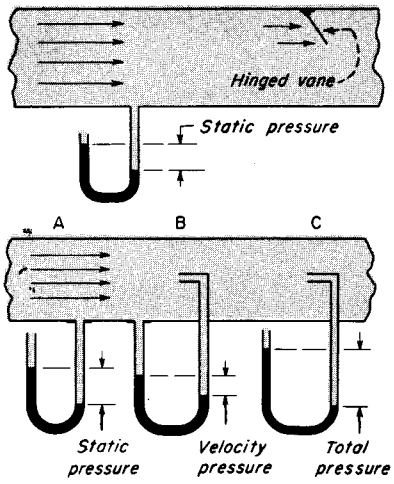
# AIR FLOW... Fans add energy to air or gas




CENTRIFUGAL FANS whirl air between the blades, have one of several blade shapes




PROPELLER FAN, *A*, can move large volumes; *B*, typical disk and airfoil shapes




FAN PRESSURES can be measured with manometers connected to or inserted in duct

# HOW FANS WORK

Moving air or gas from one point to another is an important engineering problem. Common machine for this purpose is the fan. Moving air means overcoming friction or resistance to flow. This resistance is always present whether air moves through a duct, diffuser, fuel bed or cooling tower. Since overcoming resistance is *work*, we can look on a fan as a machine that supplies air with *energy* needed to move it. What happens is that mechanical energy fed to a fan's spinning shaft is transferred to the air or gas being handled to raise its pressure and velocity enough to overcome resistance present and cause flow.

**AIR FLOW, PRESSURE, VELOCITY.** Before tackling details of fan operation, let's study how air flows Since pressures we're dealing with are normally small, easiest way to study air flow is with water-filled manometers, as shown above.

Depending on how we insert manometer in duct, we can read, not one but three different pressures: static, velocity and total pressure.

*Static pressure* is that exerted on the walls of the duct, just like steam pressure on the interior of a boiler drum. We read this by connecting our manometer tube at right angles to the duct. Static pressure is what overcomes the resistance of ducts, fuel beds, filters, etc.

*Velocity pressure* is over and above static pressure. It's caused by the impact of the flowing gas and is felt only by surfaces the gas actually flows against. Imagine a duct under pressure but with a damper on one end, closed so no air flows. In this duct we hang a hinged vane, as shown above. Since static pressure will be the same on both sides, the vane hangs vertically. But when we open the damper so air flows, vane tips back from impact of air moving against its face. This added pressure is velocity pressure.

By connecting a manometer parallel to air flow as at *C*, above, we find pressure reading is greater than the static pressure. What we are measuring is *total pressure*, the sum of static and velocity pressure.

**VELOCITY TO PRESSURE.** Now a fan is primarily a machine for accelerating or speeding up air flow. Yet very often the static pressure needed to overcome friction is more important than a high velocity. So in many cases it's necessary to convert some of the velocity energy to pressure energy. This means slowing down the velocity gradually to increase the static pressure (with a resulting decrease in the velocity pressure). This is usually done either in the fan or its discharge duct by a diverging section or diffuser. Guide vanes are also used.

**FAN TYPES.** There are in general two types of fans: (1) *centrifugal* or *radial flow*, and (2) *axial flow*.

Centrifugal fans, above left, consist of a wheel mounted on a shaft with the whole assembly rotating in a scroll-shaped housing.

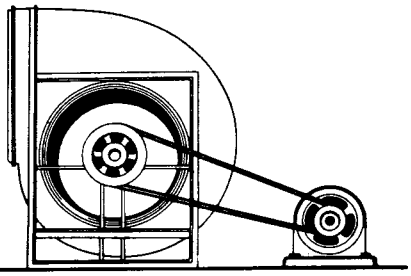
Axial-flow fans have two or more blades mounted on a shaft. Basic type is the *propeller* fan whose blades spin free or are mounted in a plain ring. *Tubeaxial* fans have a surrounding cylinder. *Vaneaxial* fans have guide vanes as well.

**MAKING AIR MOVE.** With centrifugal fans, air enters at the center or "eye" of the wheel, then makes a right-angle turn and passes between the blades of the revolving wheel. What the fan does is whirl a "chunk" of air between each pair of blades. This centrifugal action, similar to whirling a bucket of water on the end of a string, does three things: (1) "throws" the air out at a high velocity, (2) increases the air's static pressure and (3) sucks in more air at the wheel center. As the air leaves the blade tips, part of its velocity is converted to additional static pressure by the divergence of the scroll-shaped housing from the circular wheel. An outlet diffuser gives even more velocity-to-pressure conversion.

# *FAN TYPES . . . There's a right fan for every job*

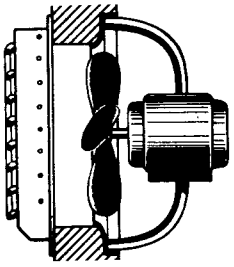
## CENTRIFUGAL

Designed to move air or gas over wide volume range. Usual static pressures go up to 25 in. water, special fans to 90 in. Wheel has straight, forward-curve, backward-curve, radial-tip or other type blades. Housing is sheet or cast metal with or without protective coat of rubber, lead, enamel, etc. Belt or direct drive



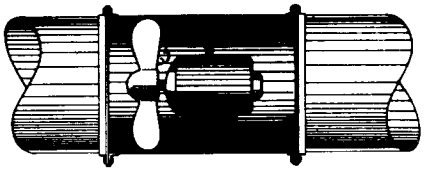
## PROPELLER

These are designed to move air from one enclosed space to another or from outdoors to indoors or vice versa in a wide range of volumes at low pressure (0 to 1 in. water, static). Automatic shutter on discharge is not part of fan. It protects fan from wind, rain, snow, cold during shutdown. Belt or direct drive



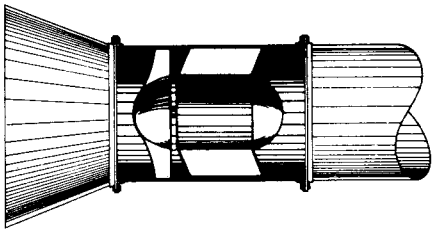
## TUBEAXIAL

Axial-flow wheel in cylinder moves wide range of air or gas volumes at medium pressures (¼ to 2½ in. water, static). Belt or direct drive. Fan may be mounted in air or gas duct. Blades may be disk or airfoil type



## VANEAXIAL

This fan has a set of air guide vanes mounted in cylinder before or behind airfoil-type wheel. It moves air over wide range of volumes and pressures. Usual pressure range is ½ to 6 in.; special designs can go up to 60 in. or higher. Wheel often made of sheet metal but cast metal is also used. Belt or direct drive



Axial-flow fans don't use centrifugal force to increase pressure. They depend on the screw action of disk-like blades or airfoils to speed air in a straight-through flow. Air is sucked in by leading edge of spinning blade to discharge with a helical motion from trailing edge. Guide vanes in vaneaxial fanes straighten helical pattern so air has little or no spin. Disk blades are often flat and set at an angle with shaft. Airfoils have special shapes (like a stubby propeller), give high efficiency.

**BLOWERS, COMPRESSORS.** No definite line exists between fans and their high-pressure counterparts — blowers and compressors. In general units for high-pressure work are compressors; those for low-pressure use are fans. Blowers usually run in the middle pressures.

## SOME DEFINITIONS USED IN FAN WORK*

**STANDARD AIR DENSITY** is 0.075 lb per cu ft at sea level (29.92 in. barometric pressure), dry air, and 70 F

**STANDARD FLUE-GAS DENSITY** is 0.078 lb per cu ft at sea level (29.92 in. barometric pressure) and 70 F

**VOLUME** handled by a fan is the number of cubic feet of air per minute (cfm) expressed at fan outlet conditions

**TOTAL PRESSURE** of a fan is the rise of pressure from fan inlet to fan outlet

**VELOCITY PRESSURE** of a fan is the pressure corresponding to the average velocity determined from the volume of air flow at fan outlet area

**STATIC PRESSURE** of a fan is total pressure minus the fan velocity pressure

**POWER OUTPUT** of a fan is expressed in horsepower and is based on fan volume and fan total pressure

**POWER INPUT** is measured horsepower delivered to fan shaft

**MECHANICAL EFFICIENCY** of a fan is ratio of power output to power input

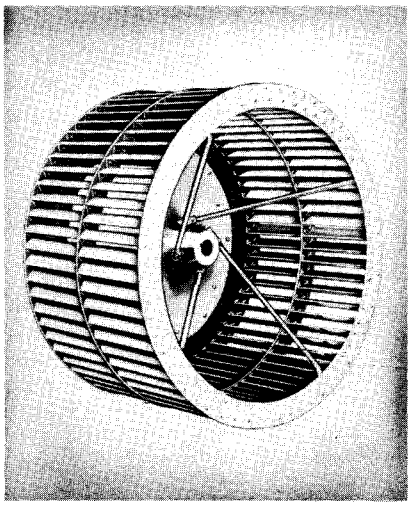
**STATIC EFFICIENCY** of a fan is the mechanical efficiency multiplied by the ratio of static pressure to the total pressure

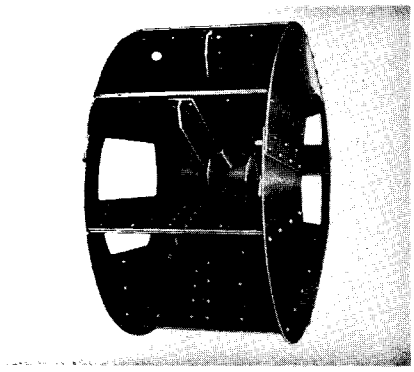
**FAN OUTLET AREA** is the inside area of the fan outlet (flange)

**FAN INLET AREA** is the inside area of the inlet collar

***From the National Association of Fan Manufacturers, Inc, (NAFM).**

# CENTRIFUGAL FANS



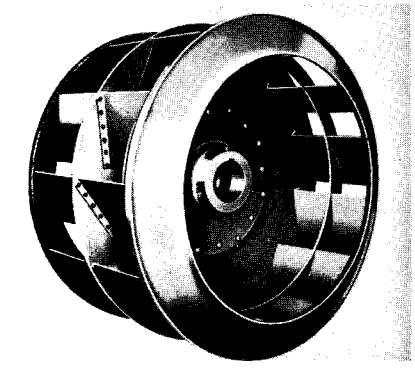


## ← STRAIGHT-BLADE WHEEL

Spider built up from hub carries about 4 to 12 steel-plate blades. Or a central plate may support the blades. Blade liners on this unit permit it to handle abrasive gas

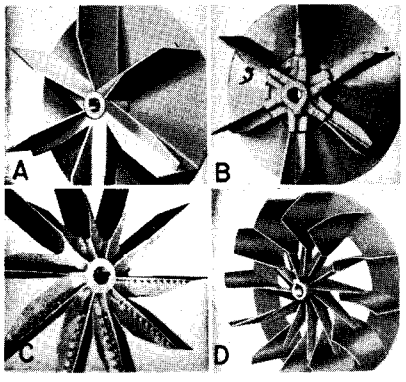
## FORWARD-CURVE WHEEL →

Backplate or central steel disk holds one end of blades; shroud ring with/without tie rods, other. Or else central arms as on straight-blade wheel. 24 to 66 blades



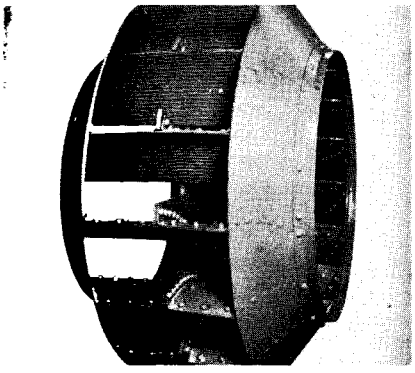
## ← BACKWARD-CURVE WHEEL

High-speed units, sturdily built. Central or backplate. Shroud ring with or without tie rods supports about 16 blades



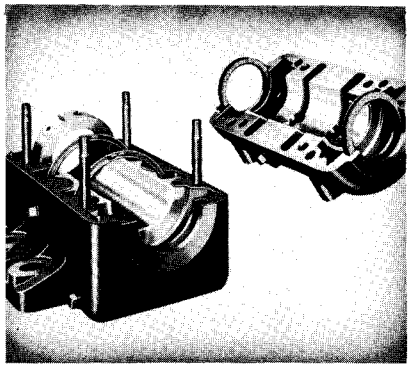

## CONVEYING WHEELS →

Welded wheel *A* and built-up wheel *B* handle wool, other stringy materials. *C* vents pulverized-fuel systems; *D* handles most any material



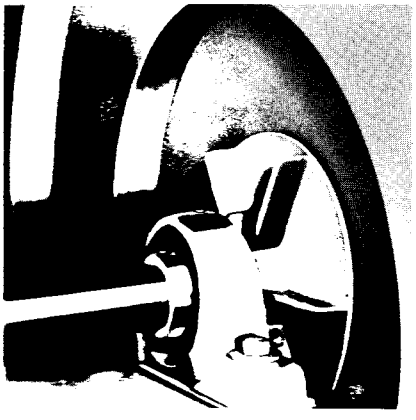
## ← RADIAL-TIP WHEEL

For solid-fuel, i-d use. Wheel has removable ribbed-liner blade faces. Center supports cut away for smooth flow. Double inlet cuts abrasion



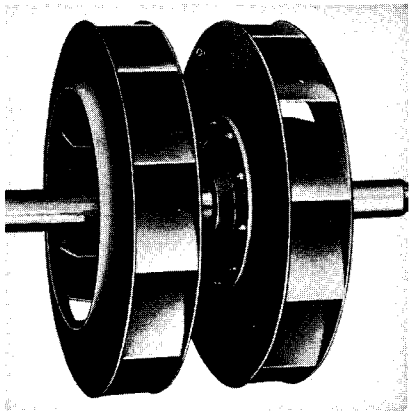
## PILLOW-BLOCK BEARING →

For draft fans all parts of bearing are split: oil rings, thrust collars and seals. Water cooling often used. Fans for other jobs may have ball or roller bearings



## ← "HEAT FLINGER"

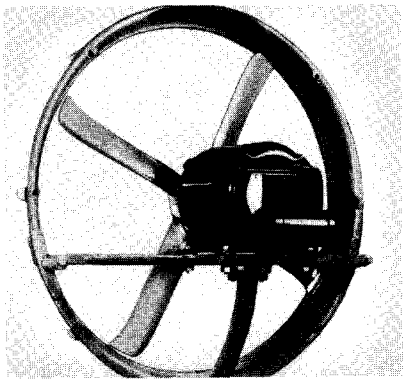
Protects bearing from heat traveling along shaft. It's a small fan firmly attached to shaft; dissipates heat from air or gas in fan



## DOUBLE WHEEL →

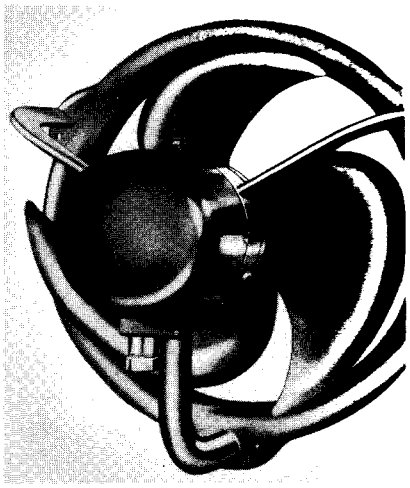
Double-inlet fan with two wheels for f-d service. Wheels are welded, heavy-duty. Backward-curve blades. Unit has good efficiency

# PROPELLER FANS



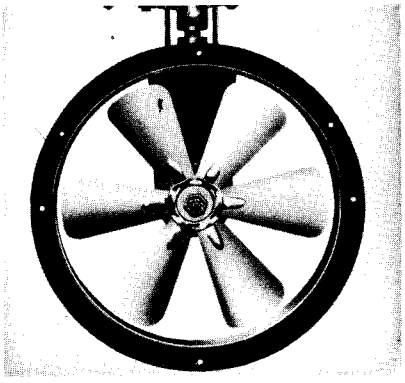
## ←FOUR-BLADED

Direct-connected totally enclosed ball-bearing motor drives fan in vertical, horizontal position. Orifice mounting ring smoothes flow



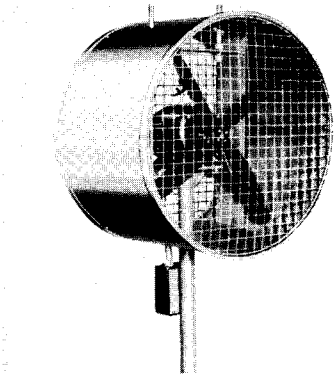
## HIGH-SPEED UNITS→

Where moderate noise is allowed, small-size fans driven by high-speed motors move large air quantities. Self cooled



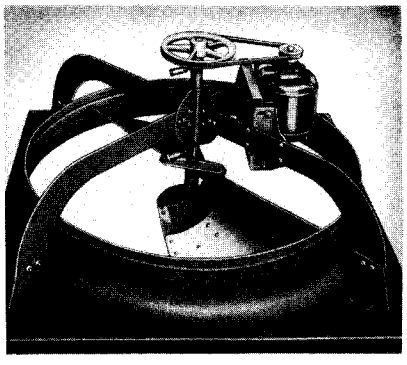
## ←BELT-DRIVEN

For fume exhaust service. Pulley, belt, enclosed in vapor-proof housing. Sheet-brass blades, cast-brass hub, enclosed motor



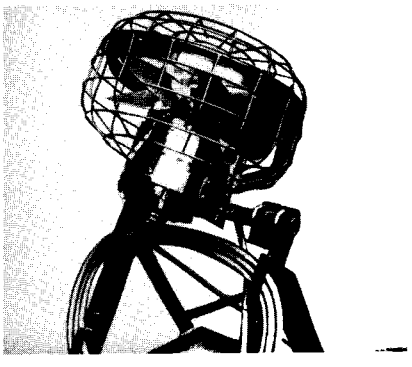
## MAN COOLER→

Portable fan cools men, products, has many other industrial uses. Steel cylinder and mesh protect blades, make fan safe



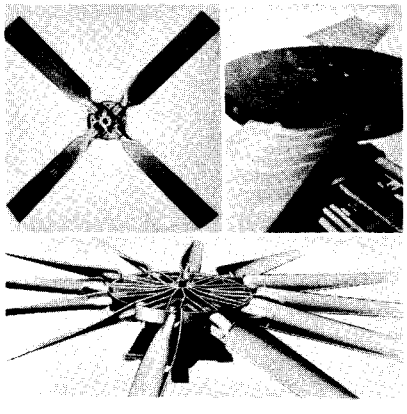
## ←TWO-BLADED

Belt-driven two-bladed propeller fan discharges air vertically up. Motor may be mounted above or below fan, as needed



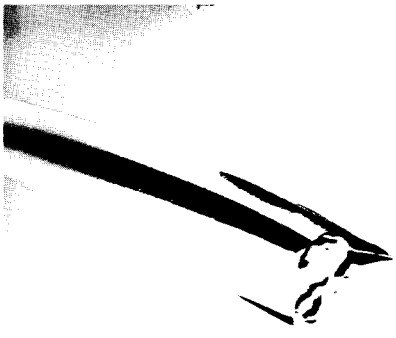
## TRANSFORMER-COOLING→

To prevent high internal temperatures and increase capacity, fans scour transformer surface with cool air. Weatherproof, adjustable



## ←COOLING-TOWER FANS

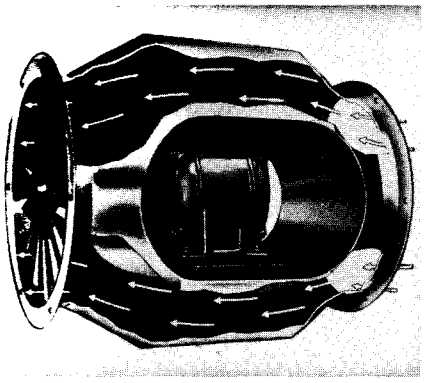
For towers and other services, fans with large diameter may be used. These have adjustable pitch, are lightweight, corrosion-resistant



## ADJUSTABLE BLADE→

This adjustable-pitch blade, one of many designs used, permits selection of most economical setting for the air-moving job being performed

# TUBE- AND VANEAXIAL FANS

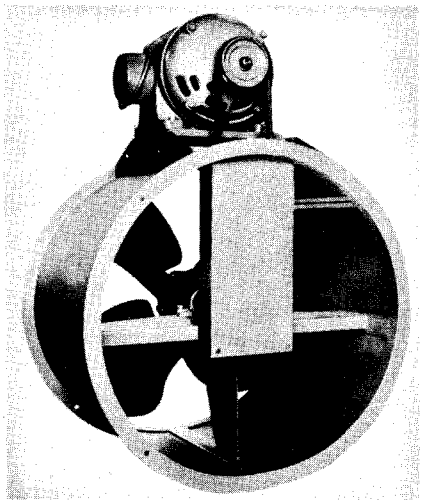


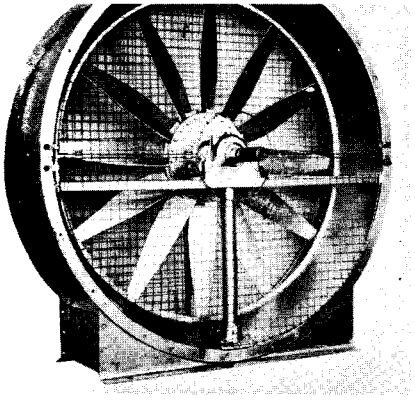
## ← DIRECT-CONNECTED

Hot, corrosive, flammable or explosive gas is exhausted by this fan with split housing. Motor in separate chamber open to atmosphere

## BELT-DRIVEN →

Where hot or corrosive air or gas is handled, motor may be outside duct with fan driven by belt. Fan cylinder connects directly to duct



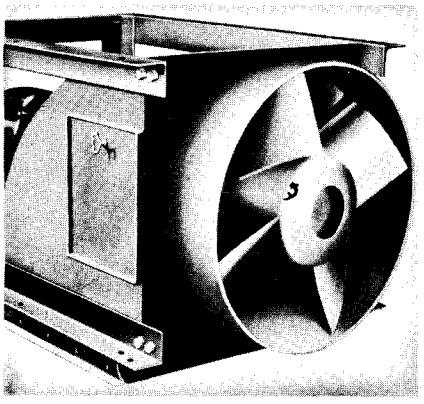


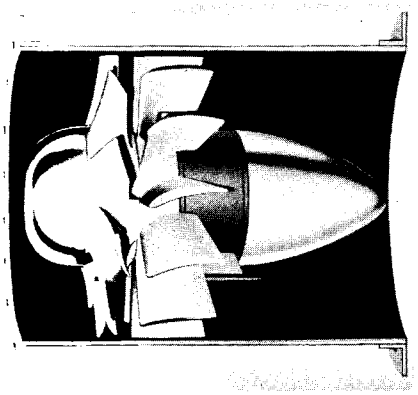
## ← FOR MINE VENTILATION

Where pressures up to 2 in. water are needed, this unit serves as an auxiliary, or for ventilating remote sections of all type mines

## ELBOW-TYPE DUCT FAN →

Supplies or exhausts air. Motor is out of air stream. Unit has self-unloading feature: as resistance increases, motor load falls



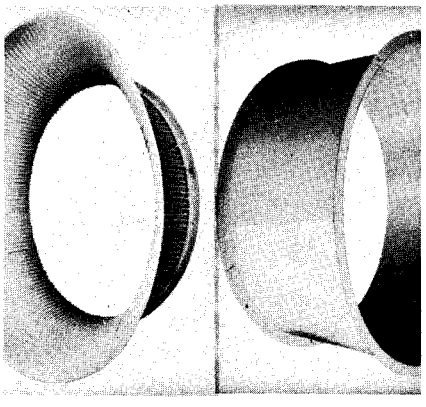


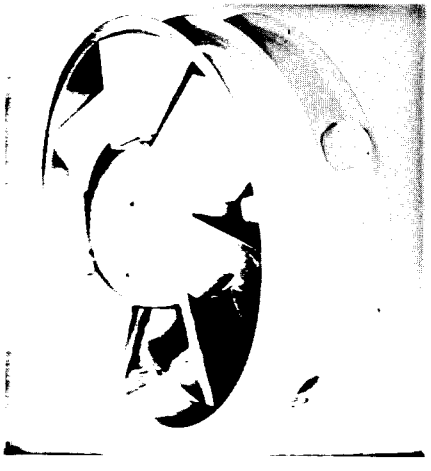
## ← AIR SUPPLY, EXHAUST

This vaneaxial fan handles moderate-temperature non-corrosive air. Vanes give discharged air straight-line axial flow at higher pressure than with propeller fan

## BELL INLET; DIFFUSER →

To reduce inlet losses, a bell, left, is used with some fans. Diffusers, right, convert discharge velocity to pressure, can save hp



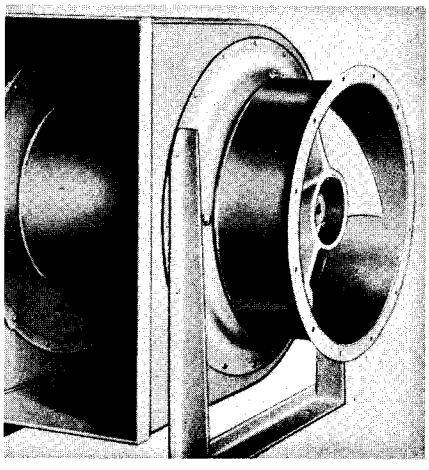


## ← VENTILATION SERVICE

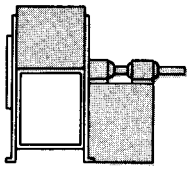
Direct-driven vaneaxial fan. Permanently sealed motor bearings; formed lightweight frame. Can be finished for corrosive work

## ELBOW AXIAL FLOW →

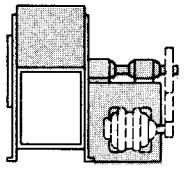
Provides 90-deg change in direction of air flow; has bearings in cone out of air stream. For paint spray booths, heat-treating ovens, fume exhaust and similar jobs



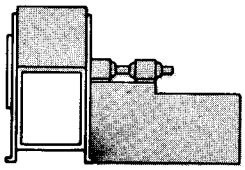
# ARRANGEMENTS



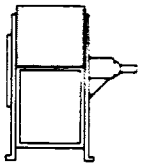
**No. 1 SW SI:** Overhung wheel, 2 bearings, belt/direct drive



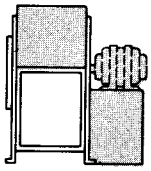
**No. 9 SW SI:** Prime mover on side of base. For belt drive



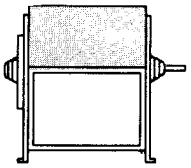
**No. 8 SW SI:** Arr No. 1 with base for driver. Belt or direct



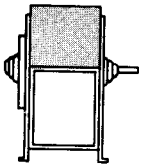
**No. 2 SW SI:** Belt or direct. bearing bracketed to housing



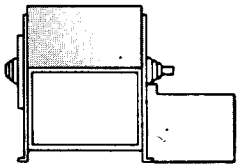
**No. 4 SW SI:** Direct, no fan bearings, the wheel overhangs



**No. 3 DW DI:** Belt or direct. Housing supports the bearings



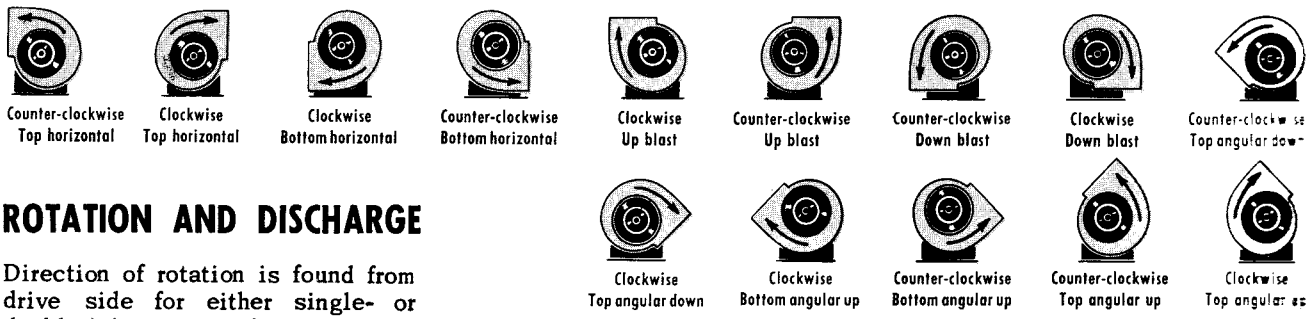
**No. 3 SW SI:** Belt or direct. Housing supports the bearings



**No. 7 DW DI:** Arr No. 3 with base for driver. Belt or direct

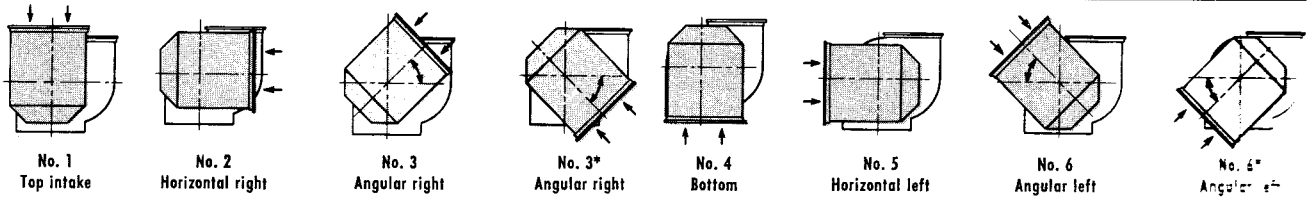
## DRIVE DESIGNATION

NAFM has set up standard arrangements for fan drive, some of which are shown above. When ordering or referring to a fan, you can easily identify by number its drive arrangement, width and number of inlets. Thus *Arr No. 1 SW SI* means a belt- or direct-driven unit with overhung wheel, two bearings on base, single width *(SW)*, single inlet *(SI)*. *DW* and *DI* mean double width and double inlet, respectively




## ROTATION AND DISCHARGE

Direction of rotation is found from drive side for either single- or double-inlet, or single- or double-width fans. Drive side of single-inlet fans is side opposite the inlet regardless of actual location of drive. For a fan inverted for ceiling suspension, direction of rotation and discharge is determined when fan is resting on floor. Designations above apply to all centrifugal fans



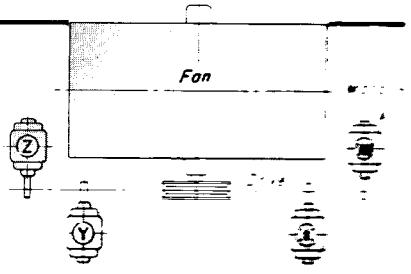

## INLET-BOX DESIGNATION

Reference is horizontal line through center of fan shaft. Air-inlet entry is found from drive side of fan. With drives both ends of fan shaft, drive side is that with higher hp. For No. 3 and 6 boxes, give angle between centerlines as shown.

*May interfere with floor framing

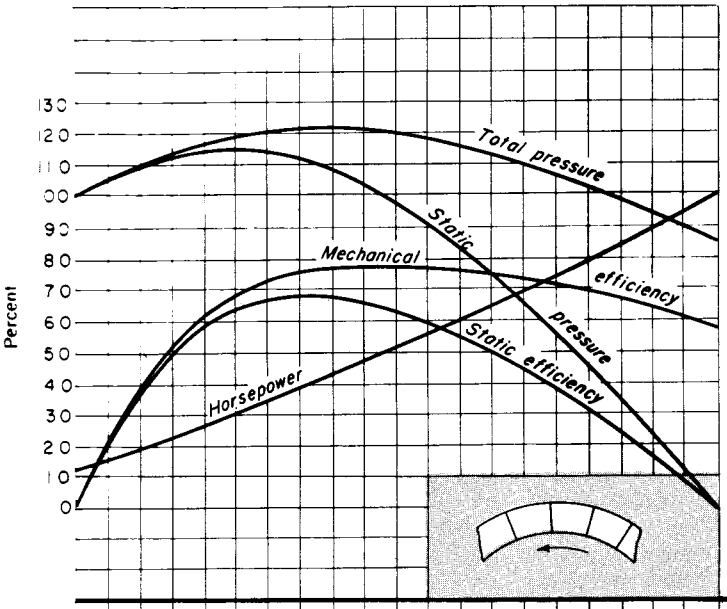
## MOTOR POSITION

For fans with belt or chain drive, motor position is given as shown at right. Face drive side of the fan and designate motor position by letters *W*, *X*, *Y*, or *Z*, as the case may be. Use the data given on this page when ordering fans and in keeping plant records



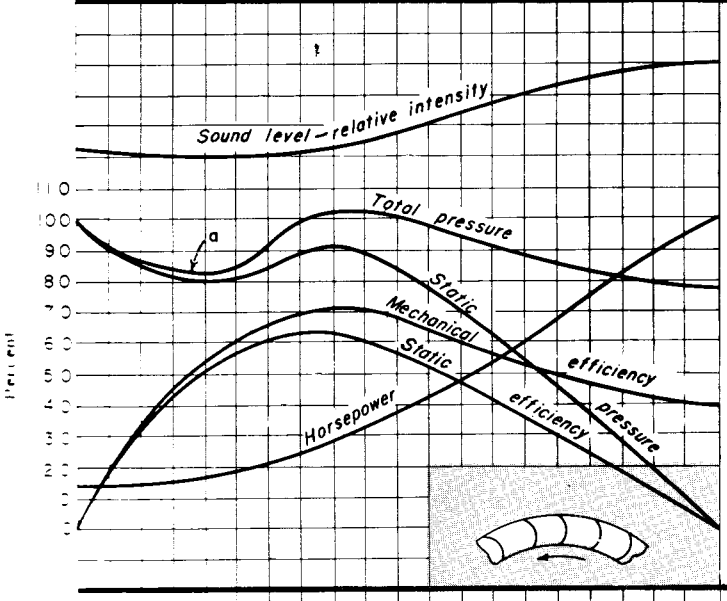
# FAN CHARACTERISTICS

***To aid in fan selection, characteristic curves plot fan pressure, horsepower, efficiency and noise level against air delivery rates ranging from no delivery***



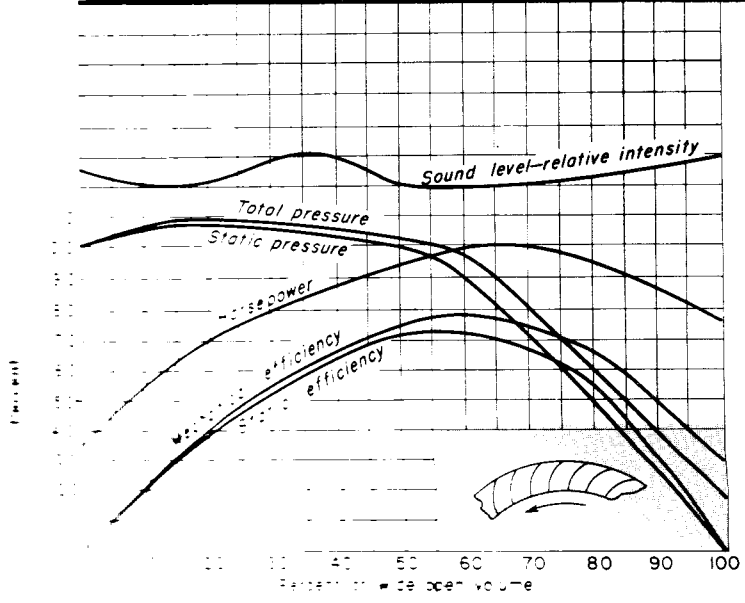

## STRAIGHT-BLADE

Discharge pressure rises from free delivery (100%) to a maximum near no delivery (0%), where it falls off. Hp input increases with fan output. Maximum static efficiency occurs near maximum pressure




## FORWARD-CURVE-BLADE

Fan pressure rises from free to no delivery with a drop, *a*, at low capacities. Maximum efficiency occurs at about maximum pressure. Horsepower input rises rapidly from no to free delivery. Sound is least at maximum efficiency and increases with higher velocity at free delivery



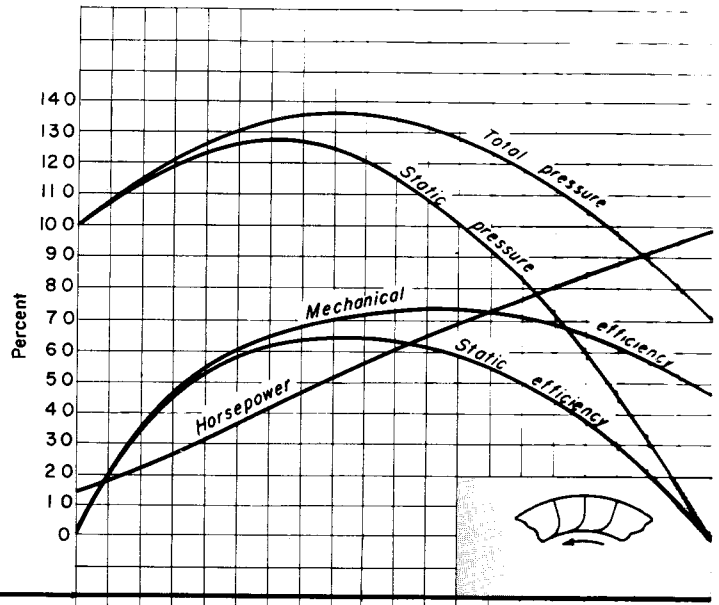

## BACKWARD-CURVE-BLADE

Fan pressure rises from free almost to point of no delivery. Horsepower is self-limiting, rising to a maximum as capacity increases, then decreasing with additional capacity rise. Fan is more efficient at maximum hp; sound is least near this point, although it changes little with capacity

*(damper closed) to free delivery (damper wide open). These curves are all on a percent basis and are typical for the type of fan or blade that is being considered*

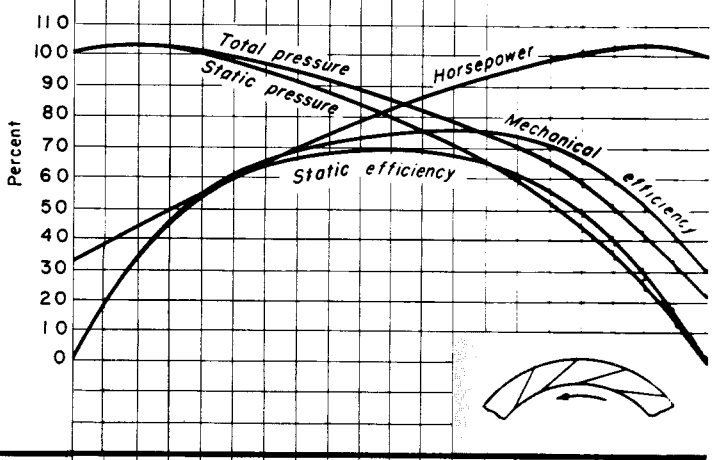
## RADIAL-TIP-BLADE

Pressure and horsepower characteristics of this fan are similar to straight-blade units. But curved heel of blade can give better efficiency, permits using shorter blades operating at higher speeds. Shock losses at wheel entrance are lower than with straight-blade design



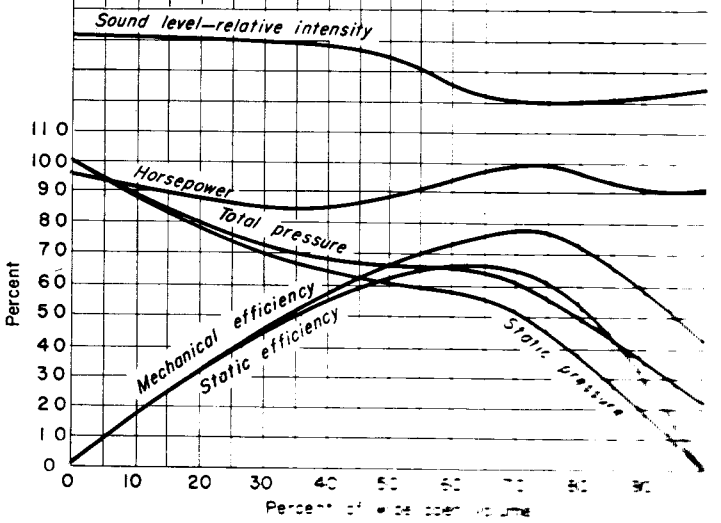

## BACKWARD-FLAT-BLADE

These are a modification of backward-curve blades. Pressure characteristic doesn't have as steep a slope, horsepower curve hasn't as distinct a hump, maximum efficiency obtainable over wider range




## AXIAL-FLOW

Depending on design, hp curve may be flat and self-limiting, as at right, or may fall from a maximum at no delivery as capacity increases. Type of guide vanes in vaneaxial fans measurably affects hp curve. Maximum efficiency occurs at higher percent delivery than with centrifugal fans



# FAN CONTROLS

***In many fan installations you must regulate output so air or gas delivered meets system needs. Summarized here are five ways to do this with advantages of each***

Fan controls include dampers, inlet vanes and louvers, variable-pitch sheaves and drives of various types – fluid, magnetic, turbine, dc, slip-ring, and two- and three-speed ac motors. Controls are grouped in three classes: (1) constant fan and driver speed with a device to alter fan or system characteristic, (2) variable-speed driver directly connected to fan to give variable fan speeds, (3) fluid or magnetic drive, or other device, that gives variable fan speed with fixed driver speed.

**DAMPERS.** These throttle air or gas flowing to or from fan. Resistance produced by damper causes fan to operate at a higher pressure than needed by system, so capacity falls off. Look at any of the fan characteristic curves, p 94, and you'll see how a pressure increase is accompanied by fall in capacity for most of the range. Curve *A*, at right, shows general change of power input with air flow in a constant-speed fan fitted with a throttling damper. Air output is proportional to damper movement after initial partial closing of damper.

Dampers are best on fans with steep horsepower characteristics. Of controls used they have lowest first cost but require largest power input to fan. Simple to operate, they have wide-range regulation, may be either manually or automatically operated and are useful with less expensive standard constant-speed motors.

**INLET VANES.** Adjustable blades or vanes fitted to fan inlet can be set to give air a spinning motion in direction of fan rotation. This spin has same effect as a change of fan speed; new pressure and power characteristics are obtained. Excess pressure used with damper control is avoided. This reduces power needed to drive fan; operating cost is lower, curve *B*. First cost of inlet vanes is moderate, they have wide-range regulation, may be manually or automatically controlled.

**INLET LOUVERS.** These are often used with induced-draft fans. They give spinning motion similar to inlet vanes. Pressure and horsepower are affected in about the same way. Operating mechanism is outside duct, safe from high-temperature gas.

**VARIABLE-SPEED DRIVERS.** Not as common as other methods, these drivers may be motors or turbines. Dc motors are easily regulated down to about 35% of maximum speed. With slip-ring motors a speed reduction of about 50% can be made cheaply. Beyond this, additional controllers are needed, increasing cost and complication of the installation. Speed reductions are made in steps as in curve *C*; intermediate regulation is done by dampers unless suitable controllers are fitted. Multispeed ac motors give speed and capacity changes of two to three to one but some form of damper or vane control must supplement them so regulating range is sufficient.

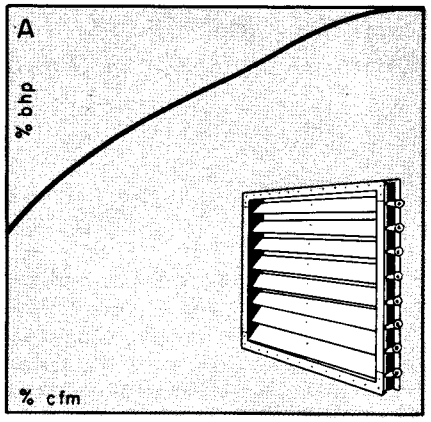
Steam turbines give good regulation of fan capacity down to about 35% of rated turbine speed. They are popular for heat balance in industrial plants. This type driver is often considered where exhaust steam is available for turbine or where turbine exhaust can be integrated in the plant heat balance.

**VARIABLE-PITCH SHEAVES.** These give speed and power changes suitable for many fans. Change may be made either manually or automatically while fan is rotating or at rest.

**FLUID MAGNETIC DRIVES.** These have similar power characteristics curve *D*. Stepless adjustable control with wide capacity range at low power input is obtained. First cost comparable to that of variable-speed motors and turbines.

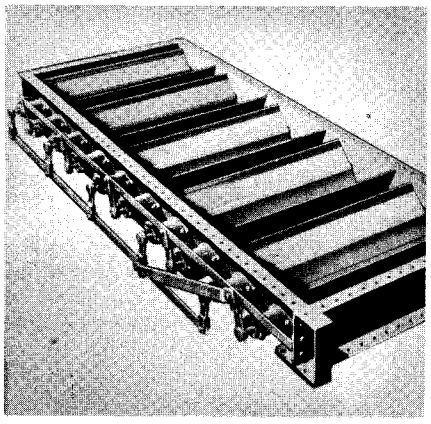
**AXIAL-FLOW FANS.** All these controls may be used with axial-flow fans. In addition, blades may be adjusted in some designs.

## CURVES SHOW

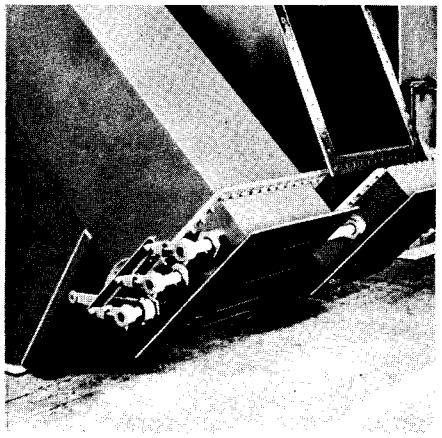



**DAMPERS throttle air or gas flowing to or from the fan, are low-cost and simple**

## BELOW ARE

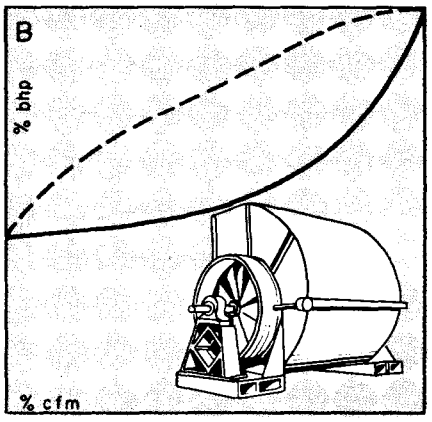


**OUTLET DAMPER for very even throttling. Blades open, close in opposite directions**

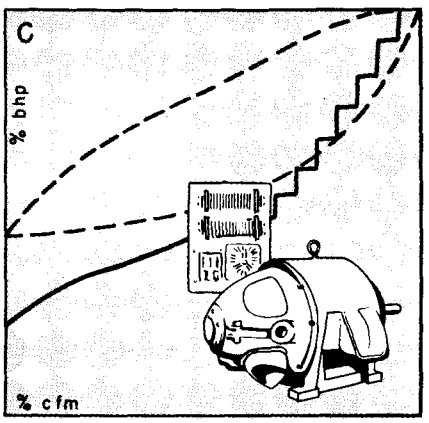


**INLET LOUVERS on i-d fan. They are more efficient than dampers, give gas a "spin"**

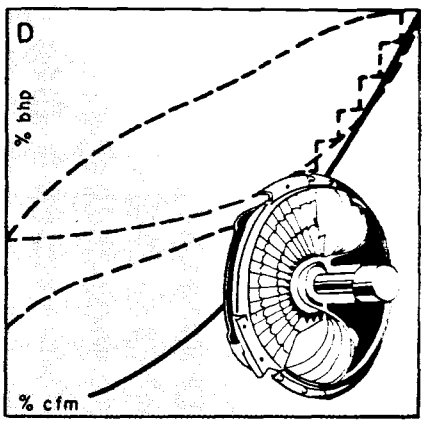
# HOW POWER INPUT VARIES WITH CONTROL TYPE




**INLET VANES** and louvers give spin to air entering fan, don't waste static pressure

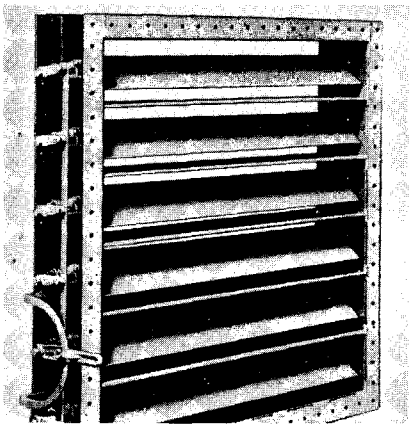



**VARIABLE-SPEED** drive, using a slip-ring motor, gives a stepped speed reduction

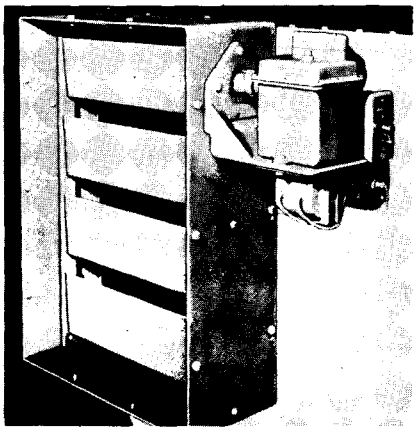



**FLUID DRIVES** and magnetic drives have like power curves, require least input

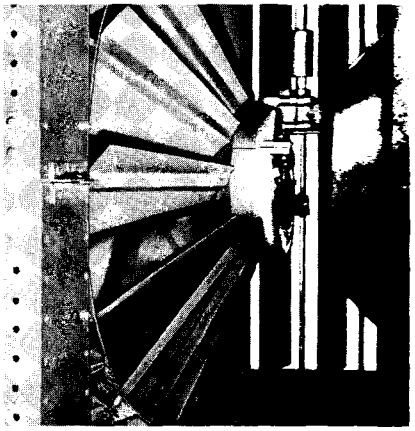
# SOME CONTROLS USED IN PRACTICAL FAN WORK



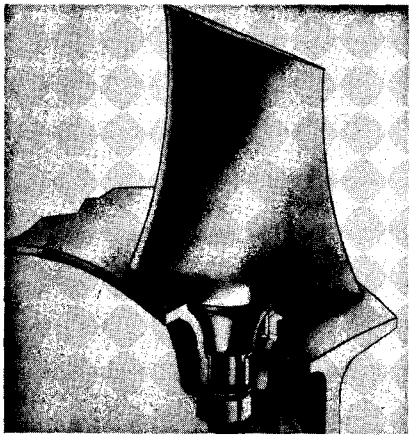
**SPLITTER PLATES** between damper blades give accurate control over entire range



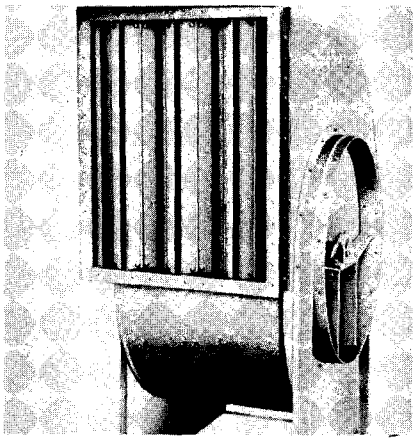
**ELECTRICALLY OPERATED** damper gives good volume control on constant-speed fan



**INLET VANES** installed in the fan inlet box are shown in their ¾ open position



**ADJUSTABLE BLADE** on vaneaxial fan gives wide pressure range, changes volume



**DISCHARGE DAMPER** on fan for ventilating or air conditioning gives good control

**PORTABLE UNIT** has [illegible] openings to [illegible]

## FAN LAWS

***Summarized here are the fan laws important in figuring performance of all types of fans. Text at right shows how to apply these laws to problems met in practice***

Symbols: $Q$ = air or gas volume, cfm; $p$ = static, velocity or total pressure, in. $H_2O$; $hp$ = horsepower input

**1. CHANGE IN FAN SPEED**

Air- (or gas-) density, system constant

(a) $Q$ varies as fan speed

(b) $p$ varies as fan speed squared

(c) $hp$ varies as fan speed cubed

**2. CHANGE IN FAN SIZE**

Tip speed, air-density, fan proportions constant; fixed rating

(a) $Q$ varies as square of wheel diameter

(b) $p$ remains constant

(c) *rpm* varies inversely as wheel diameter

(d) $hp$ varies as square of wheel diameter

**3. CHANGE IN FAN SIZE**

rpm, air-density, fan proportions constant; fixed rating

(a) $Q$ varies as cube of wheel diameter

(b) $p$ varies as square of wheel diameter

(c) *Tip speed* varies as wheel diameter

(d) $hp$ varies as fifth power of diameter

**4. CHANGE IN AIR DENSITY**

cfm, system, fan speed constant; fixed fan size

(a) $Q$ is constant

(b) $p$ varies as density

(c) $hp$ varies as density

**5. CHANGE IN AIR DENSITY**

Constant pressure and system; fixed fan size, variable fan speed

(a) $Q$ varies inversely as square root of density

(b) $p$ is constant

(c) rpm varies inversely as square root of density

(d) $hp$ varies inversely as square root of density

**6. CHANGE IN AIR DENSITY**

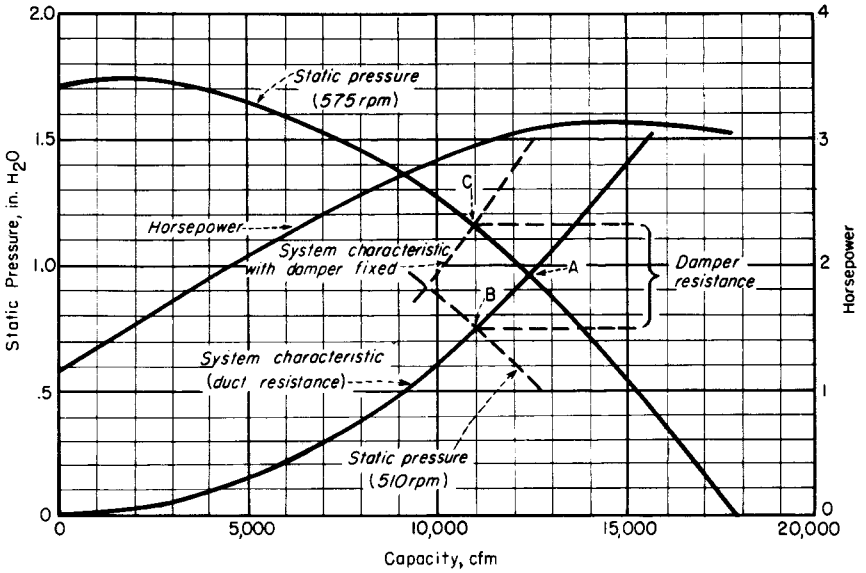
Constant weight of air and constant system; fixed fan size, variable fan speed

(a) $Q$ varies inversely as air or gas density

(b) $p$ varies inversely as air or gas density

(c) rpm varies inversely as air or gas density

(d) $hp$ varies inversely as air or gas density




**SYSTEM CHARACTERISTIC is useful in predicting what will happen when a certain fan is connected to a known system. Effect of damper and speed reduction shown**

Fan laws tell what happens to fan characteristic, p 94, when (1) speed is varied while external system remains the same, (2) when fan size is changed in geometric proportion while point of rating is fixed, (3) when air or gas density changes. The laws apply to all fans. (Size laws apply only to geometrically similar fans.) They're a useful tool.

**USING LAWS.** Easiest way to see how laws are applied is to solve some problems you're likely to meet.

**EXAMPLE:** Fan delivers 10,000 cfm at static pressure of 2 in. water when speed is 500 rpm, power input 6 hp. What's speed, static pressure, hp when fan delivers 14,000 cfm?

**Solution:** Laws in group 1 apply. So rpm = $500(14{,}000 \div 10{,}000) = 700$, SP = $2(700 \div 500)^2 = 3.92$ in., hp = $6(700 \div 500)^3 = 16.5$.

**EXAMPLE:** Fan delivers 8000 cfm at 70 F and normal barometric pressure (density 0.075 lb per cu ft) at a static pressure of 2 in. water when speed is 600 rpm, power input 5 hp. If air inlet temperature is raised to 300 F (density 0.0523 lb per cu ft) but fan speed stays the same, what is new SP, hp?

**Solution:** Use group 4 laws. Pressure = $2(0.0523 \div 0.075) = 1.4$ in., hp = $5(0.0523 \div 0.075) = 3.5$.

**EXAMPLE:** What speed must the above fan turn at to give a static pressure of 2 in. at 300 F? What will cfm and power be?

**Solution:** Use group 5 laws, Rpm = $600\sqrt{0.075 \div 0.0523} = 718$, cfm = $8000\sqrt{0.075 \div 0.0523} = 9585$, hp = $5\sqrt{0.075 \div 0.0523} = 6$.

**SYSTEM CHARACTERISTIC.** Many fans are connected to an external *system* (duct, air washer, furnace, etc) which imposes resistance on air or gas flow. Pressure needed to force air through system depends on cfm flowing. Like a fan every system has a certain relation between pressure and cfm; it can be plotted like fan characteristics and is called the *system characteristic.*

With a system of fixed resistance pressure needed varies as the square of the cfm and system characteristic has parabolic shape shown, independent of fan type.

Suppose we have a duct system that handles 11,000 cfm and needs 3/4 in. static pressure to maintain this flow. If we plot system and fan characteristics as above we find that but one condition of static pressure and capacity satisfies both fan and system. This is point *A*, intersection of the two pressure curves. It corresponds to 0.96 in. static pressure, 12,400 cfm, 3.08 hp, 575 rpm. To obtain exact flow needed (11,000 cfm, 3/4 in. SP) fan must be dampered or speed changed.

At 11,000 cfm and 575 rpm, fan pressure is 1.16 in., point *C*. So if we use a damper it must have a resistance equivalent to 0.41 in. at 11,000 cfm. Input, curve, is 2.95 hp.

If we reduce fan speed instead of dampering, 510 rpm satisfies condition, *A* moves back to *B*.

## CENTRIFUGAL-FAN MULTIRATING TABLE

Wheel diameter = 60 in. Outlet area = 20.64 sq ft

| Outlet velocity, fpm | Capacity, cfm | ½ in. SP | | ¾ in. SP | | 1 in. SP | | 1½ in. SP | | 2 in. SP | | 3 in. SP | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | rpm | hp | rpm | hp | rpm | hp | rpm | hp | rpm | hp | rpm | hp |
| 1100 | 22,704 | 236 | 2.68 | 268 | 3.73 | 296 | 4.84 | 347 | 7.29 | | | | |
| 1200 | 24,768 | 246 | 3.05 | 276 | 4.16 | 303 | 5.37 | 352 | 7.89 | | | | |
| 1300 | 26,832 | 256 | 3.48 | 285 | 4.66 | 312 | 5.91 | 359 | 8.56 | | | | |
| 1400 | 28,996 | 266 | 3.96 | 294 | 5.21 | 320 | 6.51 | 366 | 9.30 | 407 | 12.2 | 483 | 18.8 |
| 1500 | 30,960 | 277 | 4.50 | 304 | 5.79 | 329 | 7.19 | 374 | 10.1 | 414 | 13.2 | 488 | 19.9 |
| 1600 | 33,024 | 288 | 5.10 | 314 | 6.45 | 338 | 7.91 | 382 | 10.9 | 421 | 14.2 | 493 | 21.2 |
| 1700 | 35,088 | 300 | 5.79 | 325 | 7.14 | 348 | 8.66 | 391 | 11.9 | 429 | 15.2 | 497 | 22.5 |
| 1800 | 37,152 | 312 | 6.53 | 336 | 7.95 | 358 | 9.51 | 400 | 12.8 | 437 | 16.3 | 505 | 23.6 |
| 1900 | 39,216 | 325 | 7.04 | 347 | 8.80 | 368 | 10.4 | 409 | 13.9 | 445 | 17.4 | 511 | 25.1 |
| 2000 | 41,280 | 338 | 8.30 | 358 | 9.75 | 379 | 11.4 | 418 | 15.0 | 454 | 18.7 | 519 | 26.6 |
| 2200 | 45,408 | 364 | 10.37 | 382 | 11.9 | 401 | 13.7 | 438 | 17.4 | 472 | 21.5 | 535 | 29.9 |
| 2400 | 49,536 | 391 | 12.80 | 407 | 14.5 | 425 | 16.2 | 459 | 20.2 | 493 | 24.4 | 553 | 33.4 |

## VANEAXIAL-FAN RATING TABLE

All these fans turn at 1750 rpm

| Fan dia, in. | .5 in. SP | | 1.0 in. SP | | 1.5 in. SP | | 2.0 in. SP | | 2.5 in. SP | | 3.0 in. SP | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | cfm | hp | cfm | hp | cfm | hp | cfm | hp | cfm | hp | cfm | hp |
| 18 | 3260 | .7 | 2900 | .75 | 2500 | .8 | | | | | | |
| 22 | 5800 | 1.85 | 5400 | 1.9 | 4950 | 1.9 | 4250 | 2.0 | 3250 | 2.0 | 1850 | 1.8 |
| 25 | 8200 | 2.25 | 7750 | 2.65 | 7250 | 2.9 | 6750 | 3.05 | 6000 | 3.1 | 4500 | 2.9 |
| 25 | 10450 | 3.9 | 10000 | 4.1 | 9500 | 4.3 | 8950 | 4.5 | 8200 | 4.6 | 7000 | 4.4 |
| 29 | 13650 | 4.5 | 12800 | 4.65 | 11800 | 4.8 | 10750 | 4.95 | 9500 | 5.0 | 7700 | 4.8 |
| 29 | 15000 | 5.2 | 14300 | 5.7 | 13500 | 6.1 | 12700 | 6.5 | 11800 | 6.8 | 10900 | 6.8 |
| 29 | 17500 | 7.5 | 16800 | 7.7 | 16000 | 7.85 | 15100 | 8.0 | 14200 | 8.3 | 13150 | 8.4 |
| 32 | 17000 | 7.5 | 16400 | 8.0 | 15800 | 8.6 | 15200 | 9.0 | 14550 | 9.5 | 13900 | 10.0 |
| 32 | 22200 | 12.2 | 21600 | 12.5 | 21000 | 13.0 | 20400 | 13.4 | 19500 | 13.8 | 18700 | 14.1 |
| 34 | 29200 | 17.6 | 28450 | 18.4 | 27600 | 19.0 | 26800 | 19.6 | 25800 | 20.2 | 24800 | 20.8 |
| 36 | 31300 | 17.0 | 30500 | 17.8 | 29600 | 18.6 | 28600 | 19.4 | 27500 | 20.0 | 26700 | 20.6 |
| 36 | 40500 | 24.0 | 39200 | 24.5 | 38000 | 25.0 | 36400 | 25.0 | 34600 | 25.5 | 32800 | 26.0 |

# *FAN FIGURING for typical air-moving jobs*

Multirating tables like that above left are often used in selecting a fan. Giving fan test results in convenient form, they are found in many catalogs. Here's how to use them.

**EXAMPLE:** Centrifugal fan for ventilation must deliver 33,000 cfm at 1 in. static pressure, 1600 fpm outlet velocity, What is rpm, hp?

**Solution:** From table, fan that most closely meets these conditions has capacity of 33,024 cfm. Since this is so close it may be used. Under 1 in. static pressure find rpm = 338, hp = 7.91

**EXAMPLE:** Centrifugal fan with a capacity of 40,000 cfm at 2½ in. static press. is needed. Find rpm,hp.

**Solution:** Nearest capacities in table are 39,216 and 41,280 cfm. For given conditions we must interpolate. At 2 in. pressure fan speed (rpm) is $445 + \left(\frac{40{,}000-39{,}216}{41{,}280-39{,}216}\right)(454-445) = 448$.

And the horsepower input is $17.4 + \left(\frac{40{,}000-39{,}216}{41{,}280-39{,}216}\right)(18.7-17.4) = 17.9$

Similar interpolation for same capacities at 3 in. pressure gives 514 rpm and 25.7 hp. Needed rating at 2½ in. is halfway between 2 and 3 in. or 40,000 cfm is delivered at 2½ in. pressure at a speed of 481 rpm and will require 21.8 hp.

Multirating tables are suitable for most selection problems. Always have manufacturer check choice.

**VANEAXIAL FANS.** Rating table, above right, is typical for vaneaxial fans. Tables for propeller fans are similar to this one but usually include a column for capacities at free delivery (no resistance).

**EXAMPLE:** Vaneaxial fan must deliver 15,000 cfm at 2 in. static pressure. What's hp, rpm?

**Solution:** Table shows that fan which delivers 15,100 cfm at 2 in. requires 8 hp, turns at 1750 rpm and has a 29-in. diameter.

As with centrifugal fans, you can make usual selections from manufacturer's rating tables. But for special jobs, such as fans in series, consult manufacturer.

**FANS IN SERIES, PARALLEL.** Flow of air through fans in series resembles flow of current in electric batteries. When low-pressure fans are in series weight of flow is about that of one fan, total pressure the sum of the total pressures of the fans that are connected in series.

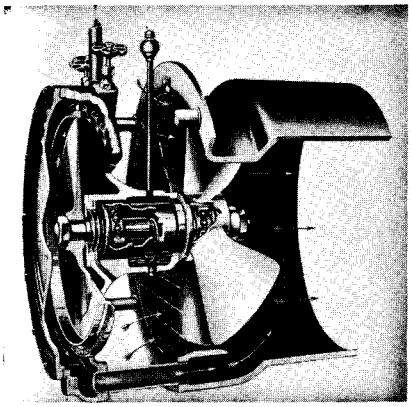
Electric-circuit analogy holds for fans in parallel too. Capacity is sum of individual capacities for a given static or total pressure.

## RECOMMENDED FAN OUTLET VELOCITIES, TIP SPEEDS

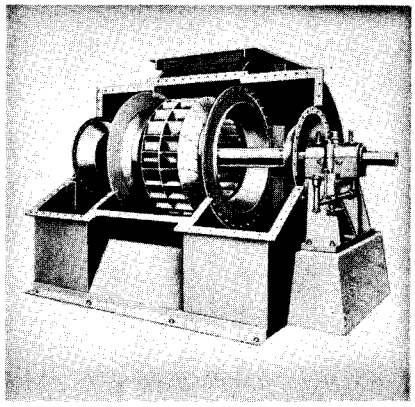
**(For air conditioning, ventilation, heating — from ASHVE Guide, 1950)**

| Static Pressure, Inches of Water | FORWARD-CURVE BLADE FANS | | BACKWARD-TIPPED AND DOUBLE-CURVE BLADE FANS | | TUBEAXIAL AND VANEAXIAL FANS |
|---|---|---|---|---|---|
| | Outlet Velocity Feet per Minute | Tip Speed Feet per Minute | Outlet Velocity Feet per Minute | Tip Speed Feet per Minute | Wheel Velocity* Feet per Minute |
| 1/4 | 1000–1100 | 1520–1700 | 800–1100 | 2600–3100 | 1100–1500 |
| 3/8 | 1000–1100 | 1760–1900 | 800–1150 | 3000–3500 | 1250–1700 |
| 1/2 | 1000–1200 | 1970–2150 | 900–1300 | 3400–4000 | 1400–1900 |
| 5/8 | 1200–1400 | 2225–2450 | 1000–1500 | 3800–4500 | 1500–2100 |
| 3/4 | 1300–1500 | 2480–2700 | 1100–1650 | 4200–5000 | 1650–2350 |
| 7/8 | 1400–1700 | 2660–2910 | 1200–1750 | 4500–5300 | 1800–2500 |
| 1 | 1500–1800 | 2820–3120 | 1200–1900 | 4800–5750 | 1900–2700 |
| 1-1/4 | 1600–1900 | 3162–3450 | 1300–2100 | 5300–6350 | 2150–3000 |
| 1-1/2 | 1800–2100 | 3480–3810 | 1400–2300 | 5750–6950 | 2350–3300 |
| 1-3/4 | 1900–2200 | 3760–4205 | 1500–2500 | 6200–7550 | 2500–3550 |
| 2 | 2000–2400 | 4000–4500 | 1600–2700 | 6650–8050 | 2700–3800 |
| 2-1/4 | 2200–2600 | 4250–4740 | 1700–2800 | 7050–8550 | |
| 2-1/2 | 2300–2600 | 4475–4970 | 1800–2950 | 7450–9000 | |
| 3 | 2500–2800 | 4900–5365 | 2000–3200 | 8200–9850 | |

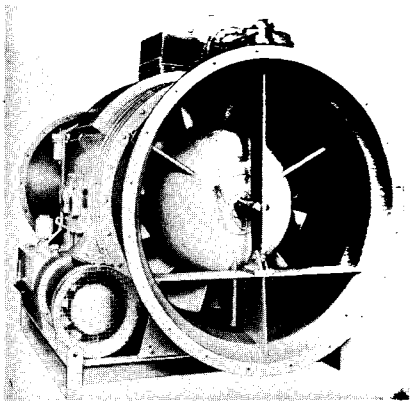
*Wheel velocity is axial mean air velocity through inside diameter of housing at point of wheel location.



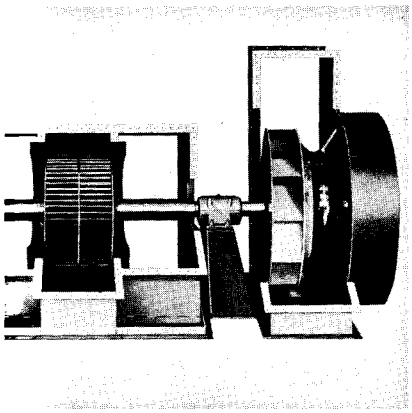
**FORCED-DRAFT turbine-driven blower supplies air needed for combustion of fuel**



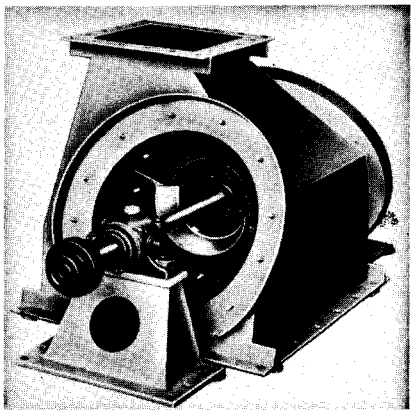
**INDUCED-DRAFT FAN, *DW, DI,* has inlet box each side of wheel, radial-tip blades**



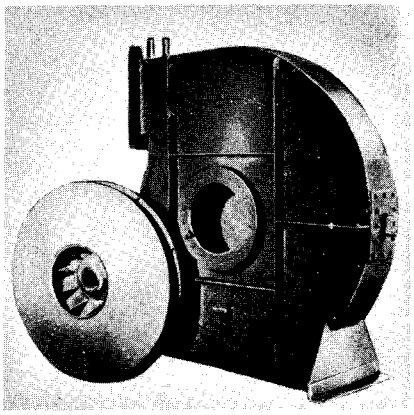
**VANEAXIAL f-d fan with variable-pitch blades; low powered, easily controlled**



**DUPLEX ASSEMBLY has i-d and f-d wheels on the same shaft, driven by fluid drive**



**FAN STACK base showing rotor, one half of split inlet cone, bearing, coupling**



**PRIMARY-AIR FAN for pulverized-fuel system blows air and coal into furnace**

# *FORCED AND INDUCED DRAFT*

Calculations for mechanical-draft fans resemble those on previous pages. Note that flue-gas density is different from that of air.

**SPECIFICATIONS.** Include these data for fan selection: (1) cfm or cfh of air or gas (2) temperature and density of air or gas (3) static pressure at fan inlet (4) static pressure needed at outlet (5) driver type (6) hours operated per year. Check with manufacturer for other data he may need in selection.

**WHAT TYPE?** Backward-curve centrifugal fan is often chosen for standard f-d use. It meets four important requirements: reserve pressure (steep head characteristic), good efficiency, high speed and ability to operate in parallel. Some f-d fans have backward double-curve blades, others that handle preheated air have forward-curve blades. Independent pedestal bearings are common on mechanical-draft fans.

Axial-flow fans are also popular for f-d. Propeller, tube- or vaneaxial units are used. Drive is turbine or motor, depending on conditions.

**INDUCED DRAFT.** Forward, back, straight and radial-tip blades give good service on i-d. For high static pressures a forward-curve fan with inlet boxes is practical because its capacity is high for given size while tip speed is low. Straight-blade wheels have few blades, low speed and can be used in parallel. Radial-tip wheels have good efficiency, moderate speed and small size for given capacity.

Some special forms of i-d fans include stack-supporting units, cinder-eliminating fans, duplex assemblies with f-d and i-d wheels on same shaft, wheels fitted with blade liners to take wearing action of abrasive gas, and fan stacks – units that combine fan, breeching and an evacuating stack. Other i-d fans have water-cooled shafts.

In one cinder-eliminating fan there are slots in scroll housing through which dust and dirt are removed. Hoppers can be fitted to fan inlet housings and dust collected returned to furnace.

Fan stacks are of various designs. In some, fan handles all gas, discharging it into a cone-shaped stack. In others a fan discharges clean air into stack fitted with a venturi section. Suction draws gas into stack from where it flows to atmosphere. Fan handles only clean air. Where gas isn't too abrasive fan may handle small amount of it or a mixture of air and gas. Efficiency is higher when handling all gas or a gas-air mixture than when handling air alone. Some fan stacks have dust collectors.

**PRIMARY-AIR FANS.** These supply air for combustion and blow coal into furnaces of pulverized-coal boilers. They are often turbine units with straight blades to give high air pressure required.

Sketches at right give hints on fan installation. Study them before putting a new fan in or relocating an old one.

**STARTING.** Unless bearings have enough lubricant, are properly aligned and dust-free, you may have starting troubles. Where air or gas temperature is 250 F or over, water cooling of bearings is often used. See that water is flowing (5 to 10 gal per hour per bearing is needed).

Before starting, shut dampers, vanes, etc. After fan is rolling adjust controls for needed pressure or draft. If fan vibrates much stop unit immediately to find cause. Watch for overheated bearings.

**STOPPING.** Shut down driver according to instructions. If fan has vane control and/or dampers, close. Let water circulate through water-cooled bearings until they're cool.

**LUBRICATION.** Oil or grease regularly. Don't add too much. Flush dirty bearings with kerosene or mineral oil; refill after cleaning.

A highly-refined uncompounded mineral oil of proved oxidation resistance is often recommended. Table gives typical viscosities.

| Air temp around bearing, F | SSU viscosity at 100 F |
|---|---|
| 32-90 | 300-350 (SAE 20W) |
| 90-150 | 500-600 (SAE 30W) |
| Above 150 | 750-1100 (SAE 50-60W) |

**VIBRATION.** Fans running unbalanced get steadily worse, can have serious trouble like burning out bearings, weakening their supports, loosening piping, springing shaft or damaging wheel. Some causes of unbalance are wear, misalignment, weak foundations, bent shaft, worn bearings and dirt on rotor blades.

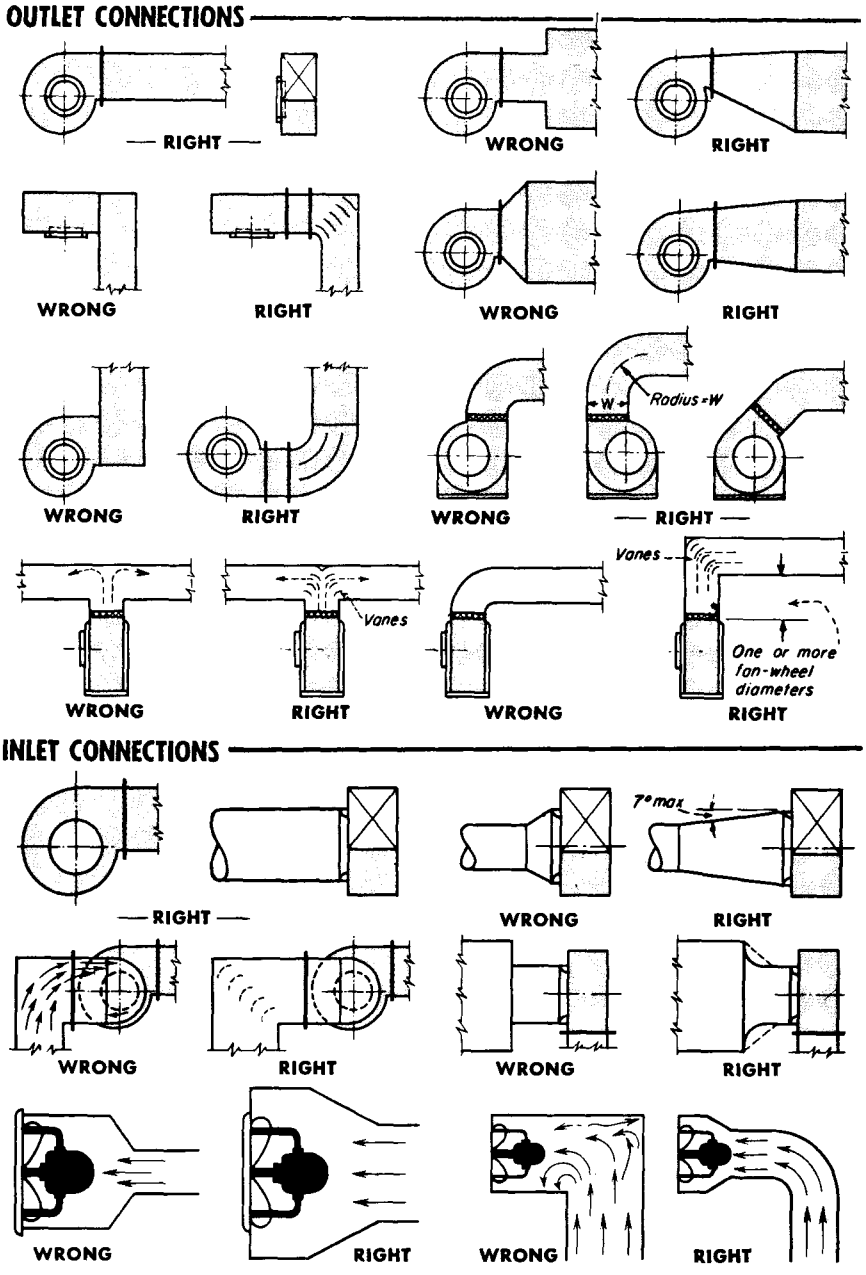
Measure amount of unbalance with a vibration meter – mechanical or electrical. There aren't any fixed rules on allowable vibration but table below gives average guide.

| Fan speed, rpm | Vibration displacement, mils, Smooth | Fair | Rough | Very Rough |
|---|---|---|---|---|
| 600 | 2 | 4 | 8 | 15-20 |
| 900 | 1.5 | 2.75 | 6 | 8-10 |
| 1200 | 1.0 | 2 | 4.5 | 6-8 |
| 1800 | 0.75 | 1.5 | 3.5 | 5-7 |

FAIR isn't bad but should be improved; balance ROUGH as soon as possible; VERY ROUGH – don't operate

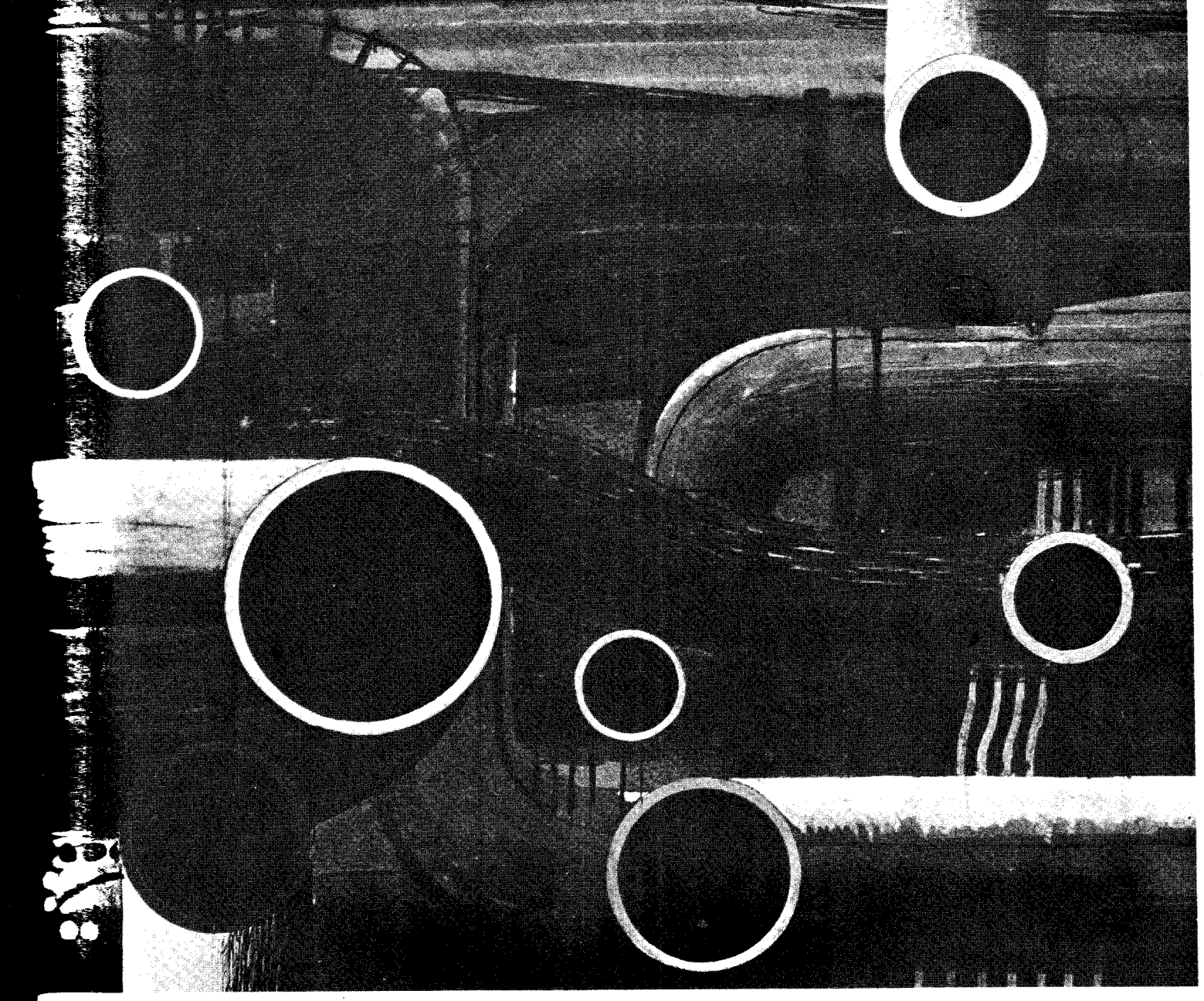
Lastly, clean fan regularly; paint where needed.

## SOME INSTALLATION DO'S AND DON'TS




## ACKNOWLEDGEMENTS

Power is indebted to the following manufacturers for supplying general information, technical data and illustrations used in preparing this special section: Aerovent Fan Co; American Blower Corp; Arex Co; Bayley Blower Co; Harvey P Bertram Co; Buffalo Forge Co; Burt Mfg Co; E K Campbell Heating Co; Chelsea Fan & Blower Co, Inc; Clarage Fan Co; Coppus Engrg Corp; DeBothezat Fans Div – American Machine & Metals, Inc; DeVilbiss Co; Diehl Mfg Co; Fly Ash Arrestor Corp; Foster Wheeler Corp; Fluor Corp, Ltd; General Blower Co; Green Fuel Economizer Co; Hartzell Propeller Fan Co; Herman Nelson Div – American Air Filter Co, Inc; ILG Electric Ventilating Co; Jeffrey Mfg Co; Joy Mfg Co; Koppers Co, Inc; Marley Co; The Moore Co, Inc; Niagara Blower Co; Prat-Daniel Corp; J F Pritchard & Co; Ripley Co, Inc; Robbins & Myers, Inc; Swartwout Co; South Bend Air Products, Inc; B F Sturtevant Div – Westinghouse Electric Corp; The Thermix Corp; The Trane Co; Westinghouse Electric Corp; C H Wheeler Mfg Co; L J Wing Mfg Co.



# PIPING

Shortage of raw piping data is not the problem today. Research reports, government test results, codes, manufacturers' catalogs and user-oriented articles in books and magazines are but a few of the sources for engineers and designers seeking piping facts. The sheer vastness of information, however, makes it difficult for an engineer to find a concise guide to piping applied in steam, compressed gas, air conditioning, refrigeration and liquid-handling systems.

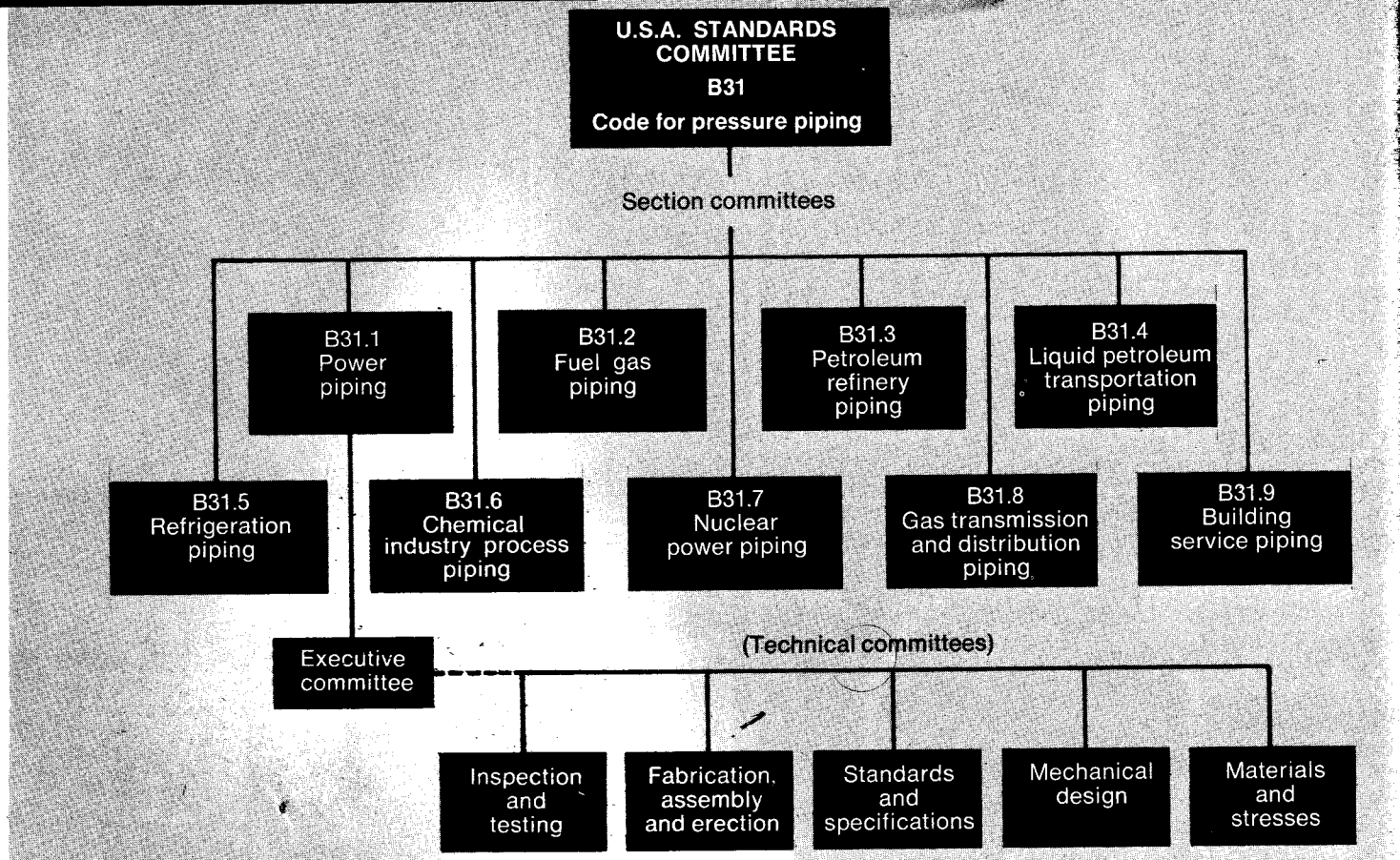
This report provides such a guide without involving the reader in readily-accessible detail. To develop a basic piping guide in 24 pages, it is necessary to omit coverage of valves, fittings, expansion joints and supports. The report concentrates on pipe alone—its materials, its methods of manufacture, its joining methods, its design into piping systems, and most important of all, today's codes and specifications. This report is designed for engineers with overall responsibility for piping systems. It is also a guide for designers who wish to have a broad view of piping systems and be able to relate their detailed knowledge of one or several narrow sectors to the entire field.

Piping codes grow in importance as public and official attention swings toward increased plant safety. Today, those wishing to understand energy-systems piping must understand the role of codes, their philosophy and reasoning.

Knowledge of metallurgy is fundamental to piping-systems design as more materials and alloys become available. To correctly explain the characteristics and performance of pipe metal in practice, a true understanding of modern metallurgy is needed.

Although many engineers avoid detailed pipe-size calculation through use of prepared charts and tables, it is the appreciation of *underlying principles* that is most important.

Joining and nondestructive testing is the final phase, and it is with this that we close the report.




**Leading code for pressure piping, B31, is ASME-sponsored. The older sections, B31.1 and B31.3, will be revised by 1970.** **B31.6 has not been published yet but is expected for this year or next. B31.7 is available in draft form for use and comment**

# ROLE OF CODES

## Piping codes now cover the major energy systems fields. Compulsory compliance and regulation loom ahead

There is a new trend in the U.S. that indicates stricter inspection and regulation of systems and devices that are potentially dangerous, even though they may have good safety records. It looks as if this trend will affect energy-systems piping, as it has petroleum- and gas-transmission piping.

**Ground rules** exist and indicate what the energy-systems engineer can expect. First of all, the basic document in all regulation of this type is the code. A code states the requirements that equipment or methods must meet to satisfy the code's chief purpose, which is usually safety.

**Code compliance** can be voluntary, or if governments adopt the code as law, it becomes compulsory. Up to now, federal, state and city governments have not drawn up general piping codes but instead depend on the important code-producing agencies. In energy-systems piping, the most important code is that shown above — United States of America Standard Institute's U.S.A. Standard Code for Pressure Piping.

USASI does not itself prepare codes; it relies on a capable sponsor (such as the ASME) which forms its technical and section committees from a wide range of experts. Professional societies and industry associations play an important part in these committees, but equally important, a balance must be maintained among piping producers, piping users, and general interest groups. The general interest groups include persons from government agencies and insurance companies, as well as unaffiliated private individuals of recognized skill. Governments, by the way, have not been eager to win places on committees; rather, they usually accept the finished code with little or no change.

**Code writers** must weigh safety against economics and enforceability. Although some technological lag is unavoidable, code writers hold this to a minimum. An example of this lag is illustrated by creep tests for new materials; results of these tests sometimes can take years.

Once issued, a code continually needs revision, interpretation and correction. The ASME, as sponsor, attaches case numbers to requests for revision and interpretation; significant cases become part of the code, entering it at major revisions.

**Complete design instructions** are not part of piping codes. However, more recent code sections, B31.7, for example, certainly contain far more extensive information on design than did the sections written in the 1950's. What all piping codes do give, how-

## These existing standards, specs and codes are practical tools for the systems designer

### ASTM Specifications are paramount

American Society for Testing Materials is the full name, but the specifications cover far more than testing. These are the most important specs and standards for energy-systems piping. They cover pipe of many materials and alloys, intended for various services. All testing methods used on pipe are described in separate specs, which have won widespread acceptance by industry. Since classification is end-use-oriented, they are easy to use and to understand.

### U.S.A. Standards cover dimensions

These standards, approved and issued by the United States of America Standards Institute (USASI), include many established practices for dimensions and other conventions in the piping field. Screw threads, pipe and flange sizes, fittings and gaskets are examples; all are vital in piping-system design. The USA pressure piping code, B31, is a vital standard for piping-system design. USASI has given B36 series numbers to many ASTM Specs.

### MSS gives many standard practices

The Manufacturers Standardization Society of the Valve and Fittings Industry issues standards for a wide range of topics. Some of these give dimensions; others establish standard practice for the design and manufacture of flanges and fittings. Still others describe nondestructive inspection and testing.

Piping code writers primarily use the dimensional data of the MSS Standard Practices. For testing, codes usually give ASTM Specification numbers.

### AWWA Standards for water piping

The American Water Works Association issues widely recognized standards for dimensions and details of cast iron, concrete and asbestos-cement pipe for water service. In addition, this body has published excellent treatises on design of water piping—steel and asbestos-cement are two types of piping covered by the standards. Piping engineers who work with underground or large-size water piping will benefit from AWWA data.

### Other ASME Codes cover related fields

The American Society of Mechanical Engineers has produced the ASME Boiler and Pressure Vessel Code and the ASME Nuclear Pressure Vessels Code. Both codes contain carefully developed requirements applicable to piping. Therefore, parts of the Boiler Code are cited in B31.1 and parts of the Nuclear Pressure Vessels Code in B31.7. There is some overlap between B31.1 and the Boiler Code.

### These groups can furnish material, too

- The U.S. Government's Federal Specifications—chiefly for piping dimensions.
- The American Petroleum Institute—on dimensions, but also much valuable information on pipe lines and welding.
- The Plastics Pipe Institute—sound data on testing and standards.
- American Welding Society — useful backup data on welding techniques.
- Pipe Fabrication Institute — valuable data on methods of joining pipe.

ever, is a complete listing of equations and practices that experience proves necessary for safety.

**Existing standards** for materials, manufacturing processes and testing are helpful to code writers and users. A standard, far narrower in scope than a code, is restricted to a specific product, such as a steel pipe for high-temperature service, or a specific operation, such as a long-term pressure test of a plastic pipe. Citation of standards and specifications is a form of shorthand for code writers, letting them list materials and processes that will be safe when used at the stress levels or in the manner specified. Citing standards does not in itself insure safety; safety becomes possible only after code writers have assigned the material or process a carefully limited field, such as allowable temperature or pressure range.

**Consensus** is a key idea in code formulation. Code-writing committees decide by consensus rather than by mere majority. Consensus means that the concerned interests are in substantial and usually unanimous agreement. Consensus and professional integrity of the code writers are important safeguards and are two reasons why the piping codes are held in high regard.

**What about enforcement?** For codes that have become law, such as the ASME Boiler and Pressure Vessel Code, enforcement machinery exists. For energy-systems piping, code compliance is almost entirely voluntary. So far, only one state, Ohio, has adopted a general piping code. Right now, code enforcement and compliance is the most controversial subject in the field. The crux of the controversy is whether close regulation of energy-systems piping is possible and whether voluntary compliance suffices.

For close regulation, inspection must be made easy. Inspection is comparatively easy in one field related to energy-systems piping — boilers — and in nuclear and fossil-fuel power piping.

**In boiler work,** several factors combine to facilitate inspection: a limited number of makers schedule, build and ship well-defined units as systems to specific sites where the boilers are erected and then remain unchanged for long periods.

**Nuclear-piping** inspection should present no difficulties. Inspection of fossil-fuel central-station piping would be harder but still feasible.

**General industrial piping,** however, with its thousands of sites, its constant and urgent changes often made at night or on weekends and its varied industry requirements and conditions, would be very difficult and costly to regulate closely.

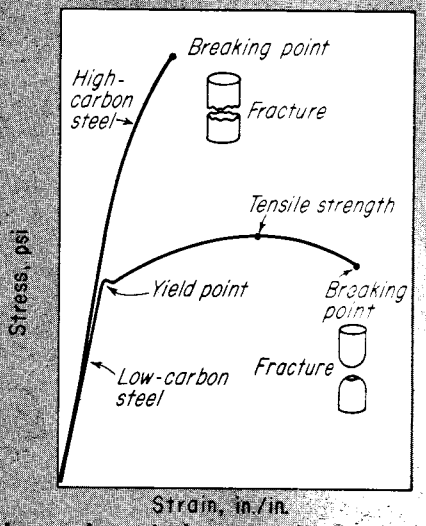
The sufficiency of voluntary compliance is debatable. True, the safety record of industrial piping has been good, but this is not enough today.

Possibly the only way to avoid compulsion is to support and use the present piping codes to the maximum extent economically justifiable. Buying pipe to ASTM standard, following code-welding practice, calculating maximum line pressures by code methods, reinforcing branch outlets in code-approved fashion—all of these are ways by which even small plants can benefit, and perhaps even stave off an unworkable regulatory setup.

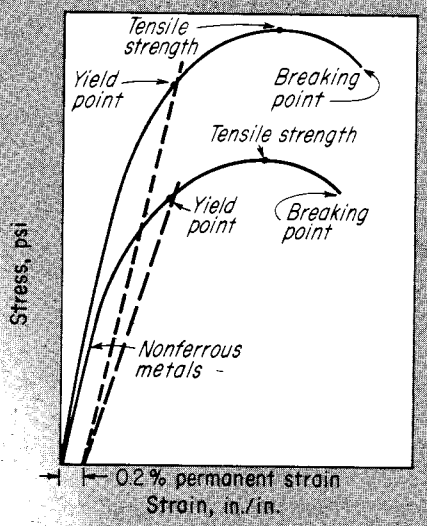
## Stress vs strain curves, taken to fracture, reveal key characteristics of pipe metals

Diagrams at right illustrate pipe metal's basic requirements: strength and ductility. Tensile stress in psi applied to a specimen stretches it, producing strain measured in in. per in. or in percent. Low-carbon steels, widely used for pipe, have a sudden yield point and then continue to develop strength but stretch faster, showing ductility. After reaching the highest stress value, called the tensile strength, the specimen necks down and fractures. High-carbon steels lack a yield point and fracture at high stress with little elongation: they are brittle.

Since nonferrous metals, most alloy steels and nonmetals lack a clear yield point, the stress value causing 0.2% permanent strain or set is arbitrarily used. Diagram at far right compares a weaker, less ductile metal (bottom curve) with stronger, more ductile metal (top).




**Low-carbon steels,** more ductile than high-carbon steel, find widest application




**Nonferrous metals** have no clear yield point. Convention used is shown above

# MATERIALS FOR PIPING

A convenient breakdown of the most frequently used metallic piping materials for energy systems is as follows: low-carbon steels, low-alloy steels and stainless steels. These steels are popular because they perform well in today's pressure and temperature ranges.

Other metals, having wide application but more specialized properties are wrought iron, cast iron, ductile iron, copper, brass, aluminum and its alloys and nickel steel.

Titanium, lead and high-nickel alloys are three examples of other metals used in energy-systems piping. These metals are not extensively used, however, because of their cost or physical shortcomings.

The more important plastic materials for piping are polyvinyl chloride, polyethylene, polypropylene and ABS. Asbestos-cement is another vital material. Use of fiber-glass-reinforced epoxy is increasing; concrete, glass, rubber and some newer plastics are also finding use.

A clear appreciation of the underlying facts of metal piping help greatly in understanding piping materials:

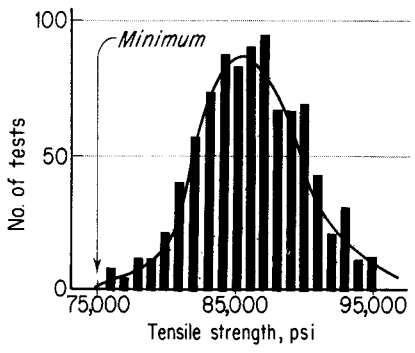
(1) Pipe wall must be round; out-of-roundness causes higher wall stress and makes joining systems harder to use. This required roundness plus the thinness of much pipe wall rule out many metal-strengthening heat treatments, such as quenching, which would distort pipe. In addition, welding, a common joining method, destroys the effect of most strengthening heat treatments.

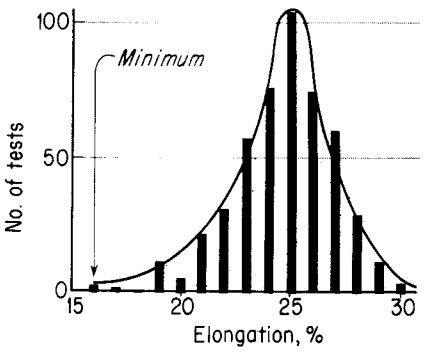
(2) Pipe size commonly used in energy systems gives accessibility only from the outside. This limits joining methods and inspection.

(3) Pipe material must be severely worked to form a tubular shape; thus, ductility and plasticity during manufacture are important. Bending and forming operations on finished pipe also necessitate ductility.

(4) Finally, pipe wall is in similar stress state throughout.

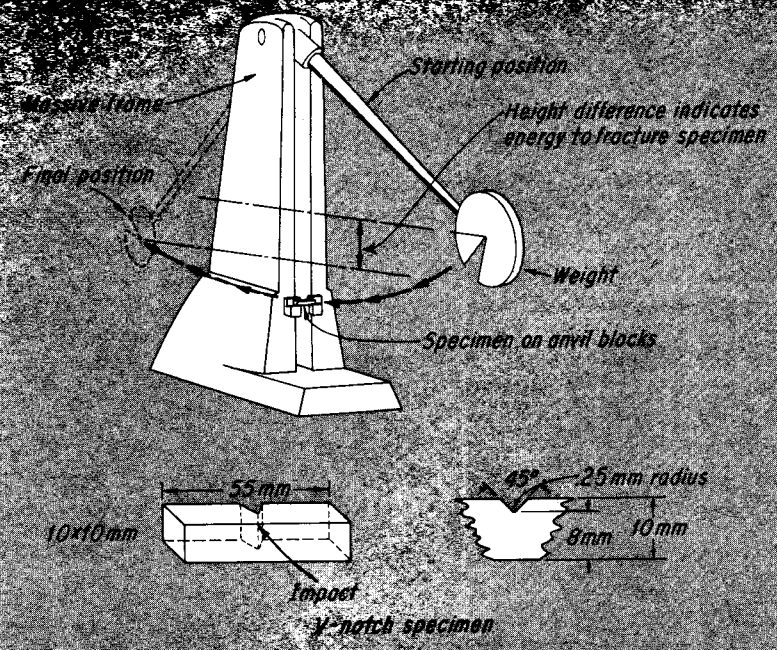
**Vital characteristics** of piping today are toughness and creep. Pipe material has toughness if it absorbs impact without splitting, even though it may deform permanently. Notch toughness is a particular form of toughness that




### Test results show dispersion

Unfortunately, piping designers must use minimum rather than average values for properties such as tensile strength and elongation. Test results on a large number of apparently identical specimens vary greatly, as shown at left, for a low-carbon steel. The difference between minimum and maximum values is often surprisingly high. The bell-shaped distribution curves are common in these large-scale tests.




**Charpy V-notch impact test gives clue to toughness**

A precise V-notch cut on one face of a small specimen causes the specimen to fracture at the notch when the heavy, pendulum-like weight strikes the specimen's face, opposite the notch. The specimen sits as a beam between the anvil blocks. The difference in the weight's starting height and final height, with friction correction, serves to calculate energy in ft-lb for fracture.

Sometimes a specimen with keyhole-shaped notch is used, but the V-notch specimen receives first preference, because its test results appear to measure toughness better.

Type of fracture is important, too. A high proportion of ductile, shear-type (taffylike) fracture area is more favorable than a high proportion of brittle (chalklike) fracture area.

ery pipe material needs; a visible notch or crack or a less parent "metallurgical notch" should not promote splitg or brittle fracture under impact or reversed stress.

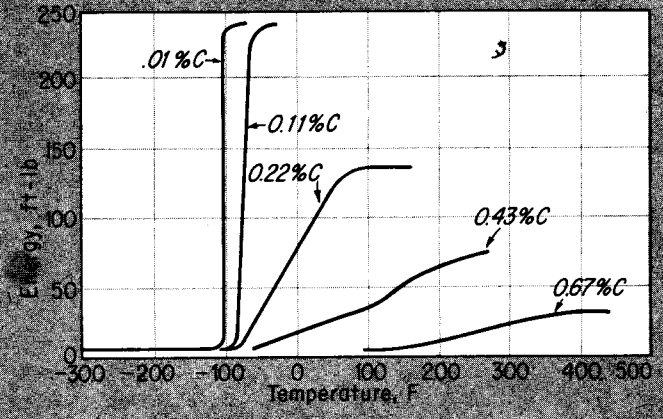
Can engineers use diagrams like those at the top of the evious page to predict toughness of a material? The swer is no. Although a large tall area under a stress-strain ve means high strength, the stress rate is slow and the ect quite different from an impact effect. Other tests, ch as the Charpy test shown above, are necessary to ge the effect of impact.

While most of these tests measure the impact energy quired to fracture a carefully designed specimen, some sts consider appearance and type of fracture.

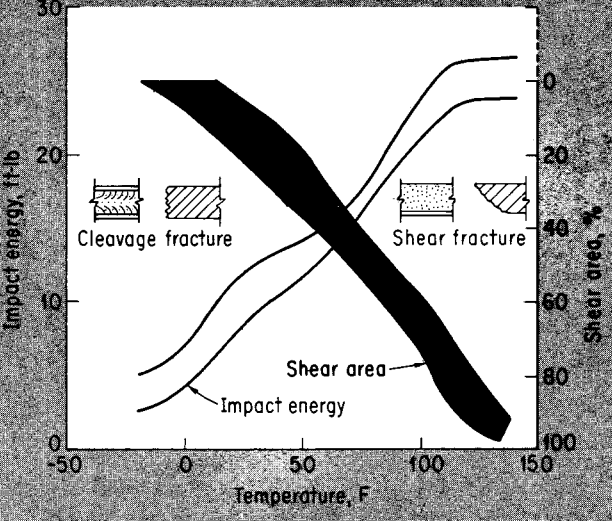
n cold weather, in refrigeration and especially in cryogenics, brittle failure is a major danger. Materials have o transition temperatures for predicting performance. e first transition temperature is the point at which pact-test values, dropping either suddenly or gradually, below a chosen minimum indicated by experience ten 15 ft-lb in the Charpy V-notch test). The second nsition temperature is that at which the specimen-fracre surface has a given percentage of shear fracture area; e rest of the area will be brittle or cleavage fractured, as e figure at lower right shows for half-size Charpy V-notch ecimens from pipeline pipe. The two temperatures can far apart, unlike the special case illustrated.

Carbon steels for cold-weather service or impact resistce are usually killed steel and may be normalized. For der service, nickel steels (3½% or 9%) are excellent; stenitic stainless steels, copper, brass and aluminum oys are used at low cryogenic temperatures.

**Creep** is the continuous plastic flow of a loaded mate. It occurs at elevated temperatures for most metals and moderate temperatures for most plastics and continues




**Low-carbon steel** in Charpy V-notch test shows better room-temperature values and sharp transition to brittle range, where impact values are same for all carbon contents shown




**Charpy V-notch tests** on line pipe show the two transitions: in impact energy and in the proportions of shear (ductile) and cleavage (brittle) fractures for the area at break point

as long as load is applied; fracture is the final result. The rate of creep is not constant under steady stress (see diagram below). Oxidation, scaling and creep are major factors blocking advance to higher-temperature steam service.

Tension tests conducted below creep temperatures do not predict a material's creep behavior. All creep study, therefore, is carried out at creep temperatures with various constant loads acting on specimens for long periods.

U.S.A. Pressure Piping Code, Section B31.1, allows stress to cause a creep of 0.01% in 1000 hours, and also limits stress on the basis of rupture after 100,000 hours. Long-duration tests are necessary since extrapolation is risky in creep study. 20,000-hour tests may be needed.

In the important second stage of creep, shown below, the creep rate is not proportional to the stress. Often the relationship is exponential, but in any case a given percentage increase in stress at a constant temperature causes a larger percentage increase in creep rate.

Once a designer or code writer has set an allowable creep rate—one that will assure trouble-free service for the expected life of the piping—his aim then must be to find materials that will carry high stress at the given creep rate and will not undergo harmful chemical or metallurgical changes. It is necessary, of course, that the material can be made into pipe and then into a piping system.

Chemical composition is the biggest factor determining creep resistance of a material—some materials are naturally better than others. At present, the austenitic stainless steels are the best suited materials available for high-temperature piping up to about 1200 F. Other factors determining creep behavior of steels are environment, grain size and previous heat treatment.

**Fatigue,** another cause of piping failure, is a result of load cycling which impresses varying or even reversed stress on the piping material. The stress, of course, is always mechanical; in piping, unlike the case in most machines and structures, the cause of the variation in stress may be thermal cycling as well as mechanical-load cycling. High-temperature steel piping may fail after comparatively few startup and shutdown cycles. Actually, high-temperature gradients through the metal, along with inherently high design stress, cause failure. Mechanical fatigue, resulting from vibration or repeated restraint during frequent startups and shutdowns, is a constant danger to piping.

**Corrosion,** an important factor to consider in most piping systems, plays an especially vital role in chemical-industry piping.

### The ferrous metals—steels and irons

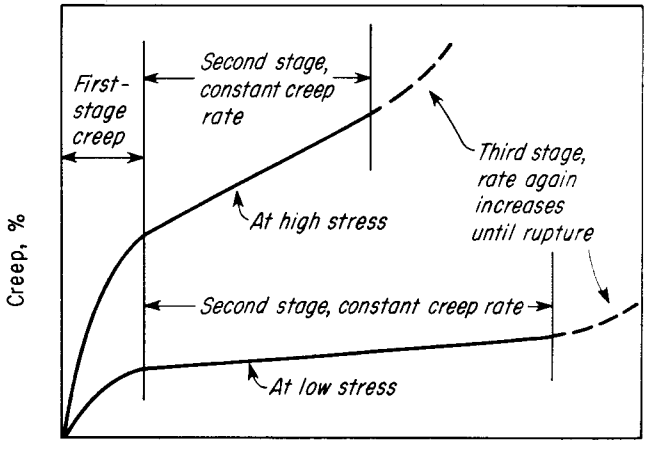
Low-carbon steel pipe leads in tonnage in energy systems, carrying steam, water, fuel oil, compressed air and other gases, condensate and effluents. Serious corrosion or erosion may occur as a result of the latter two fluids; better metal or nonmetallic material is necessary. Low-carbon steel pipe can be seamless, butt-welded, resistance-welded or filler-welded. Carbon content in low-carbon steel pipe is 0.05% to about 0.25%. In this range the steel is easily welded even with the added effect of the steel's manganese. A given percentage of manganese has about one-quarter the effect on welding that carbon has. The carbon content, although adding somewhat to strength, is not enough to harden the metal, even with the cold work or heat treatment sometimes applied.

The phase diagram, or equilibrium diagram, is important in alloy study. A phase diagram (like the one shown for carbon steel, upper right on the next page) shows each kind of crystalline grain, or phase, at various temperatures, along with carbon percentage. Austenite, ferrite, cementite and martensite are phases that occur in many steel alloys. Martensite imparts strength and hardness.

**Alloying elements beside carbon** are present in all steels, even low-carbon steel. The figure at upper left on the next page shows the effect of small additions of elements on pipe steel. Manganese, mentioned above, increases notch toughness and strength, although it lowers ductility and weldability.

**Phosphorus and sulfur** are undesirable in pipe steel and all specifications limit their percentages. Phosphorus, although an effective strengthener, makes steel brittle and may slash notch toughness. Sulfur can raise or lower the transition temperature for the 15 ft-lb Charpy V-notch test value, depending on how it is distributed. The big disadvantage of sulfur, however, is that it makes steel brittle in hot working; sulfide films are responsible.

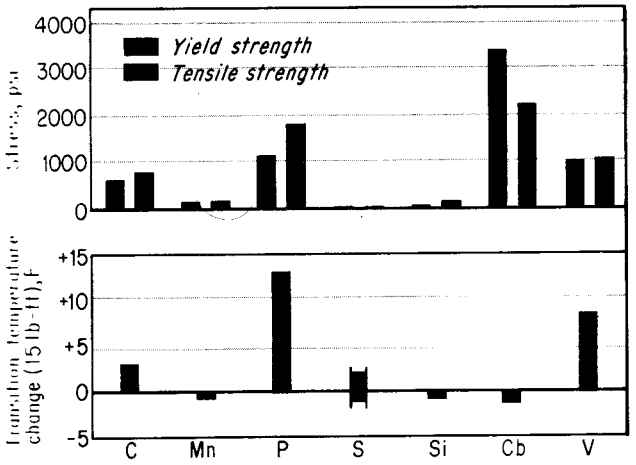
**Silicon and aluminum** in small percentages refine grain size during steel manufacture; other benefits resulting from Si or Al as minor ingredients are small. Because Al reduces high-temperature strength of pipe, silicon is preferred for




## Creep is threat to high-temperature piping

This diagram shows the three stages of creep (continuous plastic flow). At first, the percentage of creep, which is equivalent to the proportional change in length of the specimen, increases rapidly. Part of the creep in the first stage is elastic elongation and disappears when the load is removed. Second-stage creep is slower per unit of time and lasts longer.

At the end of the second stage, the creep per hour, called creep rate, begins to climb. This increase in creep rate may occur from a number of causes. The material may begin to neck down, raising the material's true stress even though the load is constant. The ambient heat or atmosphere may cause weakening chemical changes in the material. Whatever the reason, rupture soon occurs. Piping designers select stresses that will keep material below deformation at rupture. Tests are time-consuming — they sometimes take three years, but are indispensable for design.



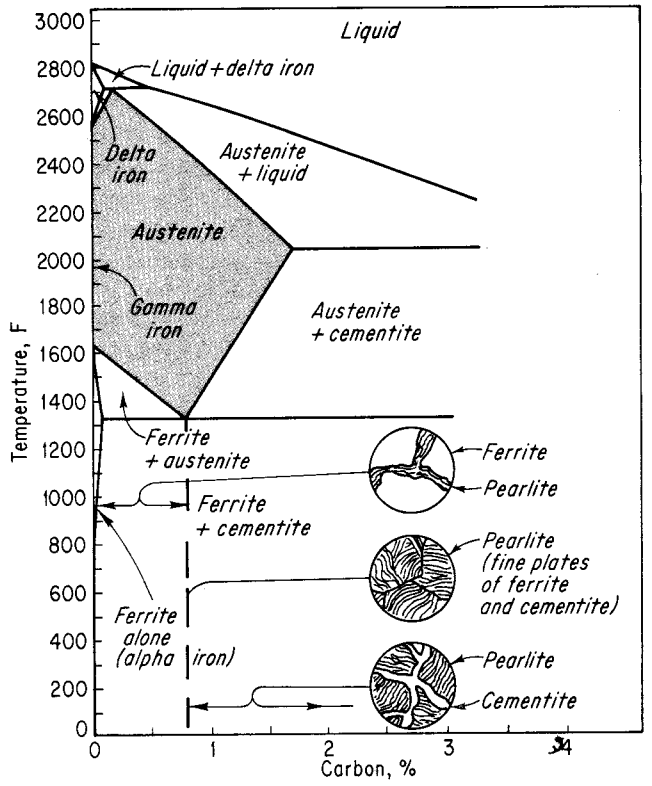

**Alloy addition**—0.01% of selected alloying elements, for example—produces varied results. Carbon has less effect than some others. P, V, and at times S lift the transition temperature

grain refining where necessary for critical steam piping.

**Chromium, nickel and molybdenum** are the key alloying elements used for pipe steel that must perform well at high pressures, at high or low temperatures, or under the corrosive conditions found in energy-systems work. Chromium and nickel increase strength, corrosion resistance and notch toughness. Molybdenum improves strength, but steels with only 0.5% molybdenum added see little use in steam systems today.

**Chrome-molybdenum steels** serve well in many h-p h-t steam applications. Alloy examples are as follows: 1¼% Cr-½% Mo; 2¼% Cr-1% Mo; 5% Cr-½% Mo. The chromium raises creep strength and resistance to oxidation, a benefit to central-station steam piping at 1000-plus F.

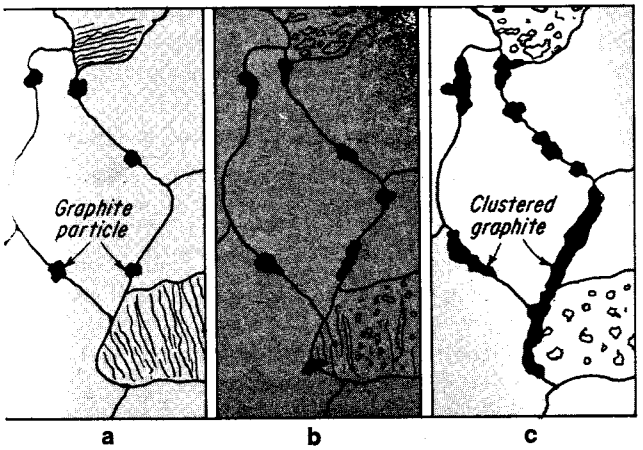
**Graphitization,** which is the slow breakdown of cementite ($Fe_3C$) to iron and graphite, can occur in carbon steels at temperatures over 775 F, in C-Mo steels over 875 F, and in low-chrome Cr-Mo steels over 975 F. Improvement in steelmaking practice has sharply reduced this danger. The figure below shows the microstructure for several cases of graphitization. The worst form can cause brittle failures that start along the weak lines of clustered graphite.



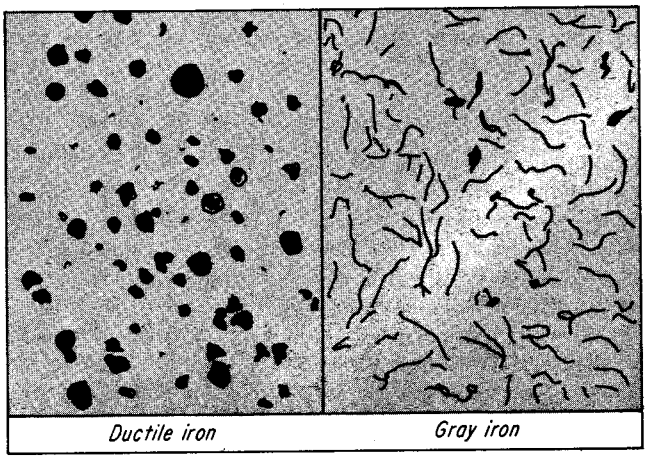

## Carbon-steel phase diagram: basic for piping

Phase diagram for carbon steel shows the various solid substances existing at different temperatures for steels with varying carbon content. Ferrite is practically pure iron, cementite is $Fe_3C$ or iron carbide. Austenite is a high-temperature form of iron containing dissolved cementite.

To follow melting of 0.5% carbon steel, proceed along the 0.5% line. The room-temperature microstructure resembles the top of the three circular sketches presented. At about 1330 F, austenite begins to form and dissolves the cementite. By 1450 F, austenite is almost the only phase present. At about 2600 F, the austenite begins to melt; melting is complete around 2720 F. Slow cooling from the austenite region results in ferrite and cementite, once again. Fast cooling (quenching) to below 600 F changes austenite to martensite, a hard material supersaturated in carbon. Martensite makes carbon steel strong but brittle.




**Graphitization,** change of steel's carbide to graphite and iron, can occur at high temperatures. Mild case at *a*, severe case at *c*




**Ductile-iron microstructure** shows nodular graphite; metal properties are better than those in gray iron (flaked graphite)

**Nickel steels,** particularly 3½% Ni and 9% Ni steels, are used in low temperature and cryogenic service.

In the last decade, steel companies have marketed low-alloy steels containing copper, nickel and other elements. These special steels are strong and have superior corrosion resistance under the moderate conditions found in energy systems. Effluent piping is one application.

**Austenitic stainless steels** (18%Cr-8%Ni) are the highest class of commonly used pipe materials. The 8% nickel causes the steel to retain its austenitic structure when cooled to room temperature. The austenite makes such steels highly resistant to corrosion, gives them good h-t creep strength and provides adequate notch toughness down to —450 F. The familiar Type 304 is the basic representative. Type 316 contains molybdenum. Type 321 contains titanium and 347, columbium; these additions stabilize the steel, preventing precipitation of chromium carbide at grain boundaries. Precipitation during welding or high-temperature exposure makes these alloys corrosion-susceptible and may necessitate heat treatment.

**In nuclear piping** carrying reactor coolant, Types 304 and 316 are in common use, sometimes in forms containing extra-low carbon, 0.03% maximum.

**Wrought iron** is practically carbon-free iron containing stringy or platelike inclusions of glasslike slag that detour and reduce corrosion caused by some of the agents found in energy-systems piping. Hot condensate and effluents are two examples of these agents. Plant experience is usually necessary to determine whether wrought iron will save money in any given application.

**Cast iron.** Although high-carbon steels (0.50% to 1.30% C) find little use in energy-systems piping, cast irons (1.7% to 5% C) are widely employed in water and effluent pipe. The B31.1 code section allows cast iron to carry steam at pressures up to 250 psi. Long and successful record of cast-iron pipe in underground and surface water and effluent lines results from its resistance to soil and atmospheric corrosion and from its reasonably good strength. Brittleness, however, is somewhat of a problem.

**Ductile cast iron** is a modified form in which the graphite (carbon) is in nodules instead of flakes, as in regular cast (gray) iron. The lower right figure on the previous page shows this difference. Ductile-iron pipe is both stronger and more ductile—10% elongation for one standard grade—than is cast-iron pipe.

## Nonferrous metals in energy-systems piping

Copper and aluminum, as alloys, are most important here. Occasionally lead, or as in recent nuclear work, high-nickel alloys, come into the picture. Copper and brass tubing predominate in heat-exchange equipment. Copper's corrosion resistance and good workability result in neat, durable piping in small water, steam and air lines in buildings, or around machinery and equipment. Thin-wall copper tubing and brass tubing fittings are used with a temperature limit of about 400 F. Aluminum and its alloys are lightweight, facilitating installation and removal of water or air lines. Aluminum-clad alloys resist corrosion better than plain aluminum alloys. Common aluminum alloys supplied as pipe are 6061, 6062 and 6063, in fairly hard tempers (T5 or T6). Copper and aluminum alloys perform well at cryogenic temperatures. Aluminum alloys usually have no transition temperature and can be used at —450 F, the limit for stainless steels.

Nickel alone is unnecessary and too costly for general use. At least one high-nickel alloy, containing 72-76% Ni, with the remainder Cr and Fe, has been proposed for primary water piping in nuclear-reactor power plants.

## Plastics and asbestos-cement are chief nonmetals

Thermoplastics become soft when heated and then recover their strength and other properties when cooled. This means that extrusion machinery can heat a material like polyvinyl chloride, force it through a ring-shaped die, cool it, and thus produce a pipe which will work well at room temperature or even in warm-water service.

**Thermosetting substances** undergo desirable and permanent changes when heated. Pipe made of this class of material usually consists of a wall system, as shown at the bottom of the next page. Epoxies, polyesters and phenolics are the chief thermosetting materials, with fiberglass or asbestos-paper reinforcement added for strength. Some reinforced plastics are claimed suitable for temperatures to 300 F in steam-return service.

As a general rule, plastic pipe is corrosion-resistant, lightweight, smooth inside and outside and easy to join. Its low heat and fire resistance is sometimes a disadvantage.

In the last few years, the thermoplastics have made huge gains in drain, waste, and vent piping, where they compete with cast iron. Acrylonitrile-butadiene-styrene (ABS) and polyvinyl chloride (PVC) are leading materials here. Building water piping is another big market for thermoplastics. PVC predominates, but polyethylene (PE) is of some value. Chlorinated PVC is better for hot water, up to about 200 F. ABS handles oil and gas. Styrene-rubber plastic, polypropylene, polybutylene (PB), and cellulose-acetate-butyrate (CAB) are other plastic-pipe materials.

Plastic-pipe testing must take creep into account even for room-temperature service. The stress sustained in a short-term burst-pressure test is usually far above the allowable stress for 1000 hours or for the 100,000 hours that is the present standard for the carefully evolved tests of the Plastics Pipe Institute (PPI). Failure in longterm tests is illustrated by bursting, weeping, or local ballooning. PPI-design stress is half the 100,000-h stress.

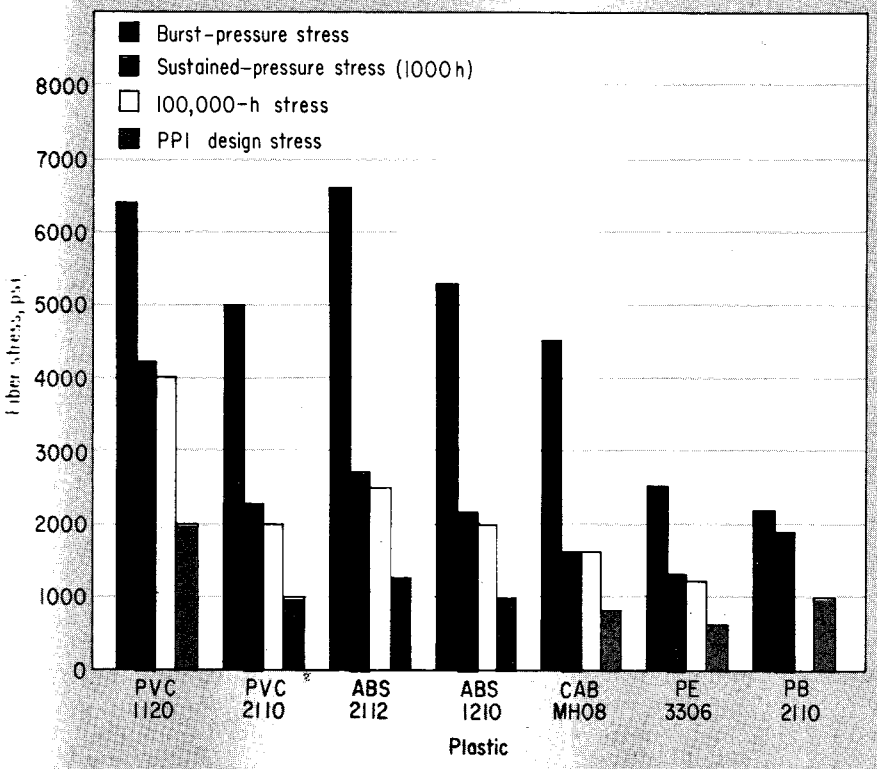
Plastic-pipe manufacturers use a four-digit code to designate their products. The first digit, usually 1 or 2, indicates the impact resistance (normal or high). The second digit gives the grade and the last two digits give the PPI design stress in 100's of psi.

**Asbestos cement** finds use in water lines. Advantages are its corrosion resistance and permanent smoothness of interior. Salt water and corrosive soils will not harm this material or cause tuberculation.

## Several components, each with its own function

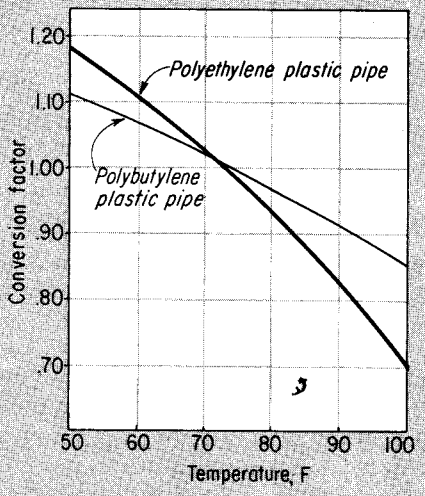
The idea of using more than one component in a pipe wall, each accomplishing its specific function, has led to full-fledged integral-wall systems. Galvanized pipe is a simple illustration: the zinc protects against corrosion while the base steel withstands stress. Cement is often used to line large steel and cast-iron water pipe to maintain a smooth interior and prevent flow reduction. Plastic liners are now put into steel or asbestos-cement pipe for corrosion resistance. In reinforced-plastic pipe, the principal load-resisting function is divided among several components, while other elements protect the stress-carrying parts, provide a smooth interior and carry auxiliary loads.

# Thermoplastics, lightweight and economical, have temperature limitations




**Thermoplastics'** long-term wall-fiber stress is far below the short-term or burst-pressure stress, but is adequate to handle most service water pressures

**Temperature** is big factor determining allowable stresses that thermoplastic pipe can carry. Polyethylene pipe is much more sensitive than polybutylene



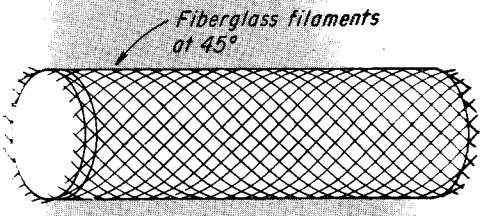

# Wall systems use separate elements to give strength and fight corrosion

Reinforced thermosetting plastic pipe requires multicomponent wall systems. Below are two such systems. The upper is conventional, with two helical winding directions for the fiberglass filaments; all filaments, embedded in the plastic matrix, take both hoop and longitudinal stress, while smooth interior plastic, formed against a mandrel, resists corrosion and helps flow.

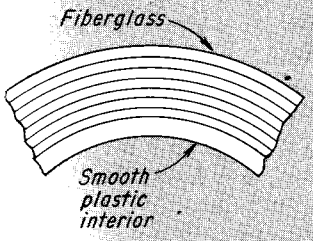
The lower system, for water pipe, is a novel attempt to reduce costs without sacrifice in performance. A nearly circumferential filament winding accepts hoop stress; inexpensive sand mortar replaces part of the polyester thermosetting resin. The smooth mandrel on which the pipe is formed gives the pipe's inner surface good flow characteristics. A longitudinal group of glass filaments handles the axial wall stress.

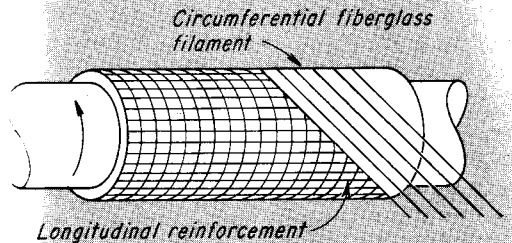
Connection and branching or tapping can be problems with pipe of the wall-system type. Bell-and-spigot connections are one solution for connection.

Illustration below is a section of an asbestos-cement pipe for underground cold- and hot-water service. The epoxy-resin lining folds back over the end to make a smooth surface for the coupling's seal gasket. Insulation and outer protective sleeve are also integral.

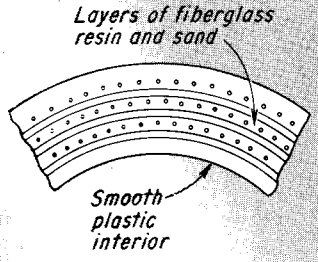


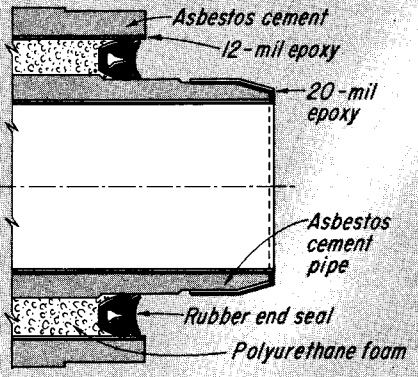

Diagonally reinforced



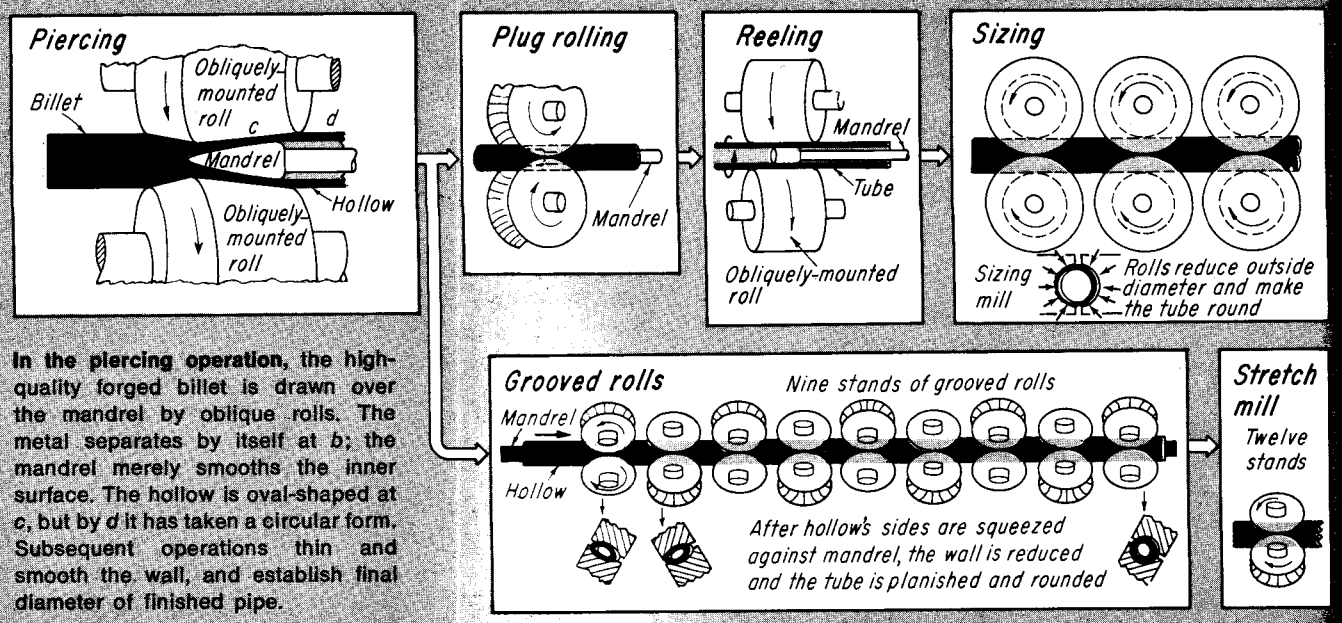




Circumferentially reinforced



**In seamless steel-tube manufacture, Mannesmann piercing makes severest demands on metal**




**In the piercing operation, the high-quality forged billet is drawn over the mandrel by oblique rolls. The metal separates by itself at *b*; the mandrel merely smooths the inner surface. The hollow is oval-shaped at *c*, but by *d* it has taken a circular form. Subsequent operations thin and smooth the wall, and establish final diameter of finished pipe.**

# HOW PIPE IS MADE

## Extrusion through dies, welding, piercing over mandrel and casting are major methods used

Every conceivable method for shaping material into pipe or tube is in practical use today. The figures on these two pages show several steel-pipe manufacturing processes selected to illustrate principles that underly the manufacture of many other materials into pipe or tube.

Because the basic stress in a pipe wall is nearly uniform, a wall without a seam has a natural advantage over a wall with a seam. This advantage does not necessarily make seamless or cast pipe more economical than welded pipe in total installed cost, however.

**Seamless steel pipe** made by the Mannesmann piercing process, shown above, requires high-quality forged metal because of the pulling and tearing action of the oblique rolls. The initial billet must have a dense outer surface free of cracks, must possess good h-t ductility and must be free of any center porosity or defects that could open on the inside during piercing.

**Extrusion** through dies is used for metal and plastic pipe. Extruders for thermoplastic pipe heat the plastic in a barrel containing a long close-fitting screw that rotates and forces the plastic out through a ring-shaped die producing the pipe. The temperatures and pressures for extrusion of steel pipe are much higher, of course, and steel-pipe extrusion machinery is far heavier and larger than plastic-pipe machinery.

The ingenious Ugine-Sejournet method, which produces high-grade steel pipe by extrusion, is not as severe on the initial forging as is the Mannesmann method; certain sensitive alloys that give trouble in the Mannesmann method can be successfully worked into pipe by the Ugine-Sejournet method. Because the dies for this process are low cost, the process is the best choice for odd sizes and small lots of special alloys. Extrusion processes put material under heavy compression in all directions, giving a uniform and fine structure. After steel extrusion, cold-reduction operations follow; these bring the tube to size.

Piercing and drawing, shown at bottom of next page, is another way to make high-grade steel pipe.

**Welded steel pipe** is made by butt welding and electric-resistance welding, both shown on the next page. In large pipe and in some alloy pipe, filler metal is used to produce the seam. Codes rate a butt-welded longitudinal seam at a lower efficiency than an electric-resistance or filler-metal weld.

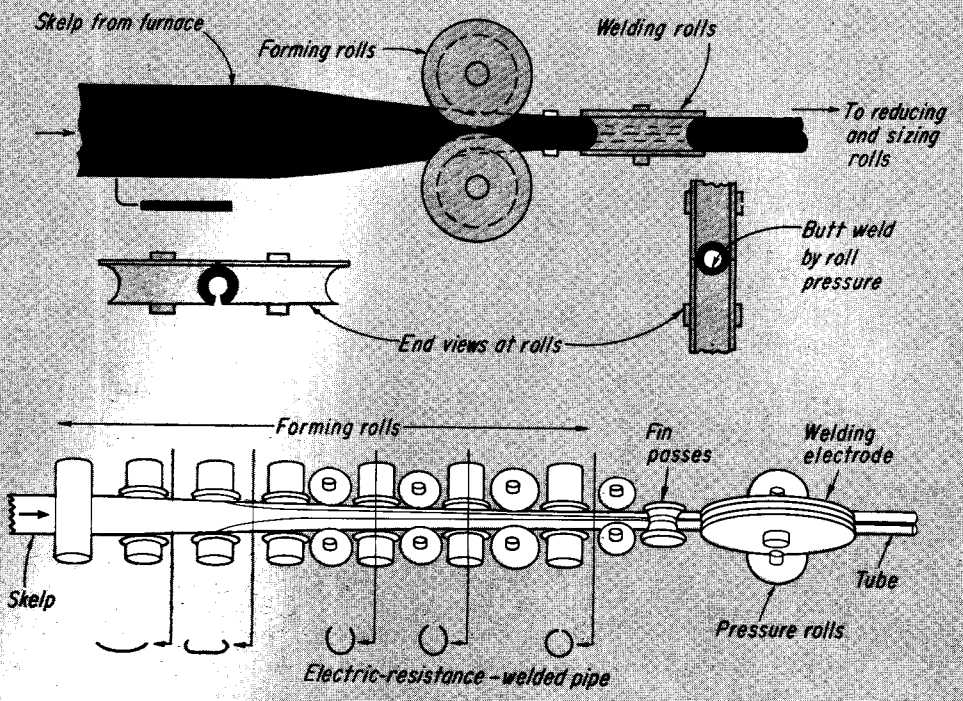
High-production processes turning out pipe in a limited selection of outside diameters can justify large numbers of roll stands and big inventories of rolls. Small lots or special sizes are usually made by die methods, by boring of forgings or by centrifugal casting.

Casting produces not only cast-iron and ductile-iron pipe but also carbon and alloy-steel pipe. The latter is often centrifugally cast in spinning molds that generate high forces, throwing the metal toward the mold surface and leaving impurities and blowholes near the inside, where subsequent machining removes them.

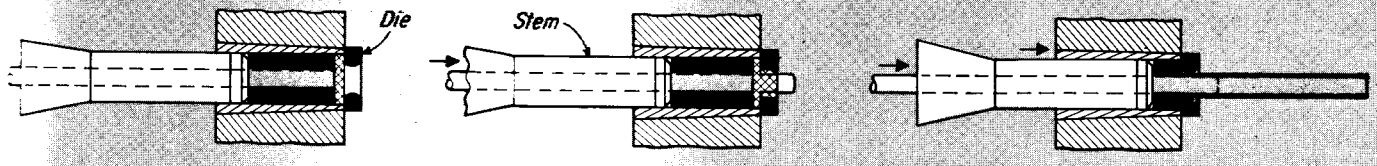
Reinforced plastic pipe, shown on the previous page, and asbestos-cement pipe are two types made by winding on a mandrel. The former uses glass filament, the latter a wet film of asbestos, cement and silica. In reinforced plastic pipe, good bond between resin matrix and reinforcement is essential. Sometimes air voids and delamination can occur.

## Butt welding and resistance welding add no metal to pipe

These are two high-production methods for making standard sizes and weights of pipe. In butt-welded pipemaking, forming rolls shape narrow plate into a nearly full circle; the hot metal is then squeezed together to fuse the sides of the seam. In the electric-resistance welding method, fin-pass rolls trim the facing edges of the curled skelp to prepare them for welding and to get accurate dimensions. Pressure rolls force the joint edges together and the tube passes a welding roll of two electrode halves with electric insulation between them. Since the two halves straddle the pipe joint, welding current passes between the electrodes through the pipe joint, where resistance to current flow produces the desired heat to fuse the metal. Excess metal is then trimmed off on outside and inside of the weld seam.



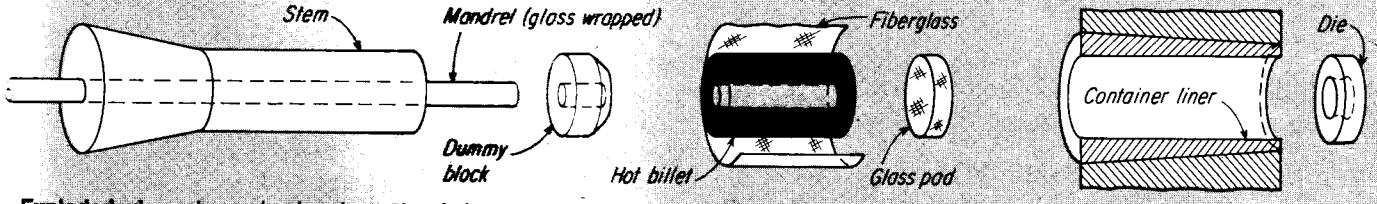

## The Ugine-Sejournet extrusion method forces hot metal through molten-glass-lubricated die




1 **Billet heat** melts glass pad, lubricating the die before extrusion

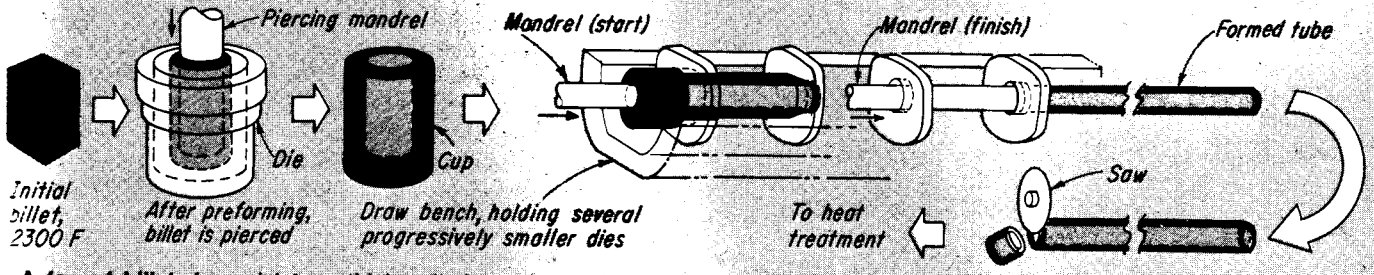
2 **Stem and mandrel** continue advance; glass pad helps cool die

3 **Advancing stem** begins to extrude metal between die and mandrel

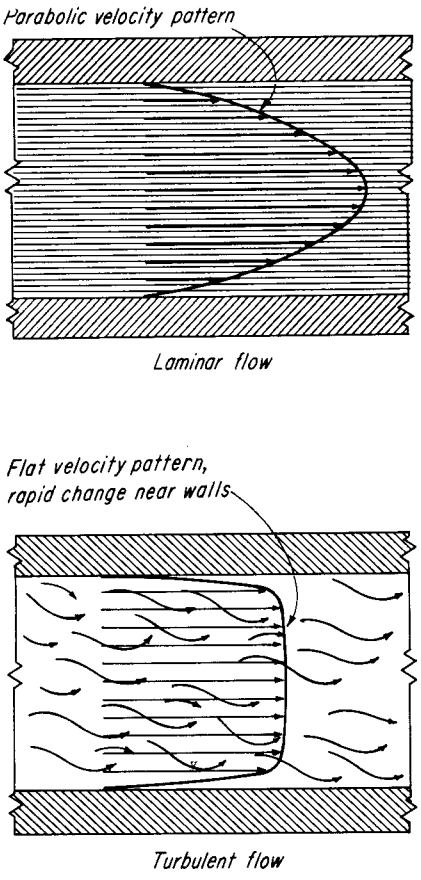



**Exploded view** shows basic elements. A heavy stem pushes against a dummy block which in turn forces out the fiberglass-wrapped hot billet as a tube between the die and a closely centered glass-wrapped mandrel in previously made billet hole

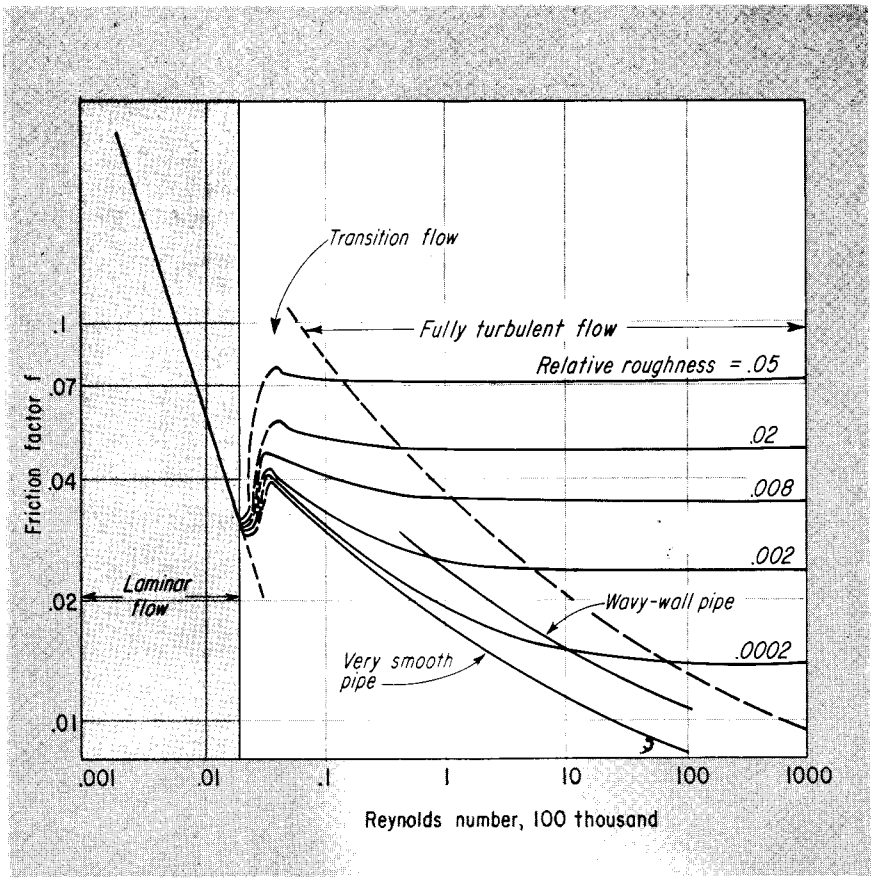
## Piercing and drawing, used for many alloy types, reduces wall thickness by successive dies




**A forged billet,** formed into a thick-walled cup by a piercing mandrel that squeezes excess metal upward in the die, goes to the drawbench after inspection. The cup, still red-hot, is placed on the end of a long mandrel that advances through a series of dies progressively smaller in diameter. These removable dies are mounted rigidly in the heavy framework of the drawbench. The dies push the metal in the thick-walled cup back over the advancing mandrel and thus produce a long tube which emerges from the final die. The closed front end of the tube is removed and the tube receives heat treatment, such as normalizing, before end-finishing and hydrostatic test. This method is adapted to handling small lots of alloy pipe.




**Flow pattern** — laminar or turbulent — depends on flow conditions in pipe




**Friction factor** for use in basic flow formula is linked directly to internal surface, roughness and Reynolds number: Latter calculated from velocity, viscosity, and ID

# DESIGNING THE SYSTEM

## Begin with flow conditions to determine pipe size, calculate for strength, and then select pipe; codes and specifications will assist here

Inside pipe diameter, together with temperature, pressure, corrosion and erosion, determine a line's cost. The inside diameter must be sufficient to maintain pressure drop and sometimes velocity within reasonable limits.

Flow in pipe is either laminar or turbulent. Figure (upper left) shows characteristics of the two types. Oils may flow in laminar manner while water, steam and air are generally turbulent. The figure (upper left) on facing page shows examples of this.

**Pressure-drop** calculation is simple for laminar flow, more complicated for turbulent flow. Charts and nomographs help a great deal, but the designer should understand the fundamentals, too.

Viscosity, density, velocity and wall roughness are the most important factors. Viscosity of a fluid is measured in terms of the force necessary to pull a fluid layer of area A at velocity V, relative to a stationary surface at distance D:

$$F = (\text{a constant})\ A\ (V/D)$$

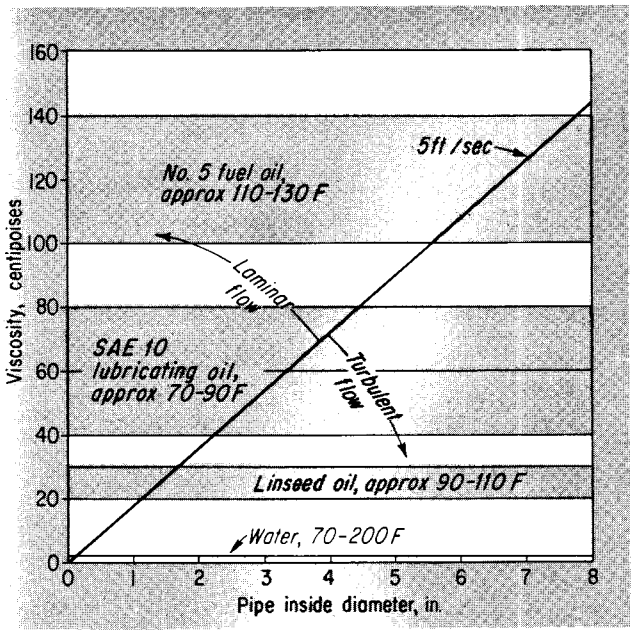
The constant is called the absolute viscosity. Poises and centipoises are units commonly used here; water's absolute viscosity at 68.4 F is 1 centipoise. The constant becomes kinematic viscosity when divided by fluid density.

The relative roughness of a pipe is the height (usually .0002 to .01 in.) of the tiny asperities on the wall, divided by the inside diameter.

The factor determining type of flow — smooth and orderly laminar, or confused turbulent — is the ratio of the scattering influences to the restraining influences. Scattering influence increases as diameter and velocity increase; restraining influence increases as viscosity increases. A crowd of people in a small passage is a rough analogy. Those who walk slowly in a narrow passage tend to maintain straight lines, while people running at various speeds in a wide passage tend to intermingle and take irregular paths. Relatives or friends would tend to remain together, however, in a "viscosity" effect. In piping, the ratio of the two types of influence is called the Reynolds number ($N_r$):

$$N_r = \frac{\text{velocity x inside diameter}}{\text{kinematic viscosity}}$$

In piping, flow is laminar below a Reynolds number of about 2000; it is turbulent above approximately 8000. A transition region lies between these two numbers that is partly laminar and partly turbulent.




## Oil flow is often laminar in energy systems

The velocities of liquid in energy-systems piping are generally low: the range is roughly 2-20 ft/sec. These velocities make pressure drops reasonable. For high-viscosity oils, lower velocities are chosen, of course, increasing the probability of laminar flow. Gases flow much faster and have low viscosities (a fiftieth to a hundredth that of water), so that their flow is almost always turbulent.

Water, too, is nearly always turbulent in energy-systems piping, with a Reynolds number often beyond one million.

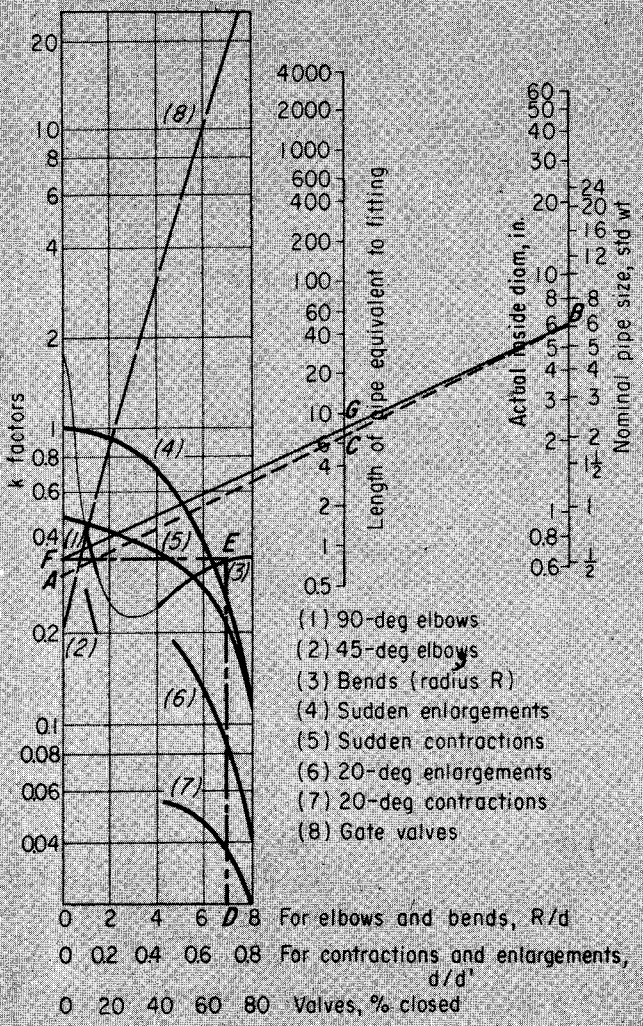
Theory shows that pressure drop in a pipe depends directly on pipe length (L) and the square of fluid velocity ($v^2$). Also, as the figures at the upper left on the preceding page indicate, the bigger the ratio of inside circumference (measured by in.) to cross-sectional area (in sq in.) the more the wall drag effect will be felt: All other factors being equal, pressure drop will be greater for a smaller pipe. The basic equation in one form becomes:

$$\text{pressure drop, psi} = \frac{f}{144}\,\gamma\,\frac{L}{D}\,\frac{v^2}{2g},$$

with $\gamma$ as the density in lb/cu ft, D the inside diameter in ft, L the length in ft, v the average velocity in ft/sec and g is the gravity acceleration (32.2). The friction factor in this equation, f, varies as shown in the graph at the top of the previous page. In the laminar region, $f = 64/N_R$. In the fully turbulent region, f depends on pipe's relative roughness and on $N_R$, but at sufficiently high Reynolds numbers, f depends solely on relative roughness.

Because the basic equation requires trial-and-error solution, many researchers have developed approximation equations and have prepared charts, like those shown on this and the next two pages, to ease calculation. One example is the Williams and Hazen formula for water flow: head loss in ft per 1000 ft $= 3022.6\ v^{1.852}/C^{1.852}D^{1.167}$

## Use chart and table for equivalent length




**Take a 6-in. inside diameter pipe, 80-ft long, with a 90-deg welding elbow and a 3-ft 6-in. radius bend. For the elbow, use a k-factor (one which indicates the flow resistance of a fitting) of 0.32, obtained from the table below for standard fittings. Draw a line from k=0.32 (A on the chart k-scale) to 6 in. inside diameter (B) on the nominal pipe-size line. The equivalent length is at C: 6½ ft. For the bend, R/d=42/6=7. Enter chart at D, where R/d=7 and go up to E on curve 3 for bends. Go left to F on the k scale and construct a line from F to B on the nominal pipe-size scale. The equivalent length is at G—7½ ft.**

**Adding straight length and equivalent length of fittings gives 80 + 6½ + 7½ = 94 ft, the length to be used in flow calculations. If a piping run has more than one diameter, calculate equivalent length and pressure drop separately for each diameter's run and then add pressure drops.**

| Fitting | k factor | Fitting | k factor |
|---|---|---|---|
| 45-deg welding elbow | .21 | 45-deg lateral through branch | .75 |
| Gate valve, open | .21 | 90-deg standard screwed elbow | .92 |
| 90-deg welding elbow | .32 | Submerged discharge | 1.00 |
| Welding tee, through run | .40 | Welding tee, through branch | 1.40 |
| 45-deg screwed elbow | .42 | Screwed tee, through branch | 1.60 |
| 180-deg welding return | .42 | Fabricated tee, through branch | 1.80 |
| Screwed tee, through run | .50 | 180-deg close-screwed return | 2.00 |
| Fabricated tee, through run | .50 | Swing-check valve, open | 2.50 |
| Submerged entrance | .50 | Angle valve, open | 4.00 |
| 90-deg long-sweep elbow | .60 | Globe valve, open | 10.00 |

# Two nomographs, one for liquids and one for steam and gases

Charts make this simple to use. Williams and Hazen's C, in the formula(p S-13)varies from 140 (smooth pipe) to 60 (rough pipe).

When calculating pressure drop and line size, first choose a desired velocity such as:

| | |
|---|---|
| water | 3 to 10 ft/sec |
| l-p steam | 20 to 150 ft/sec |
| h-p steam | 100 to 300 ft/sec |

These are guide values only; allowable pressure drop is usually a more reliable final criterion. Next, calculate inside pipe diameter in. from

$$\sqrt{\frac{0.409 \times \text{gpm}}{\text{v (ft/sec)}}} \quad \text{or} \quad \sqrt{\frac{3.06 \times \text{cu ft/min}}{\text{v (ft/sec)}}}.$$

For steam flow, use specific volume to calculate cu ft/min from lb/h. Most piping systems include fittings and valves, so the next step is to find the equivalent straight-pipe length of all pipe, valves and fittings in the system. The chart and table on the preceding page will assist.

To determine pressure drop per 100 ft of equivalent length, the designer can now either calculate from basic or empirical equations or he can use charts and tables for a quick solution.

The two sets of charts on these pages are an example of aids for the latter course.

## Liquids

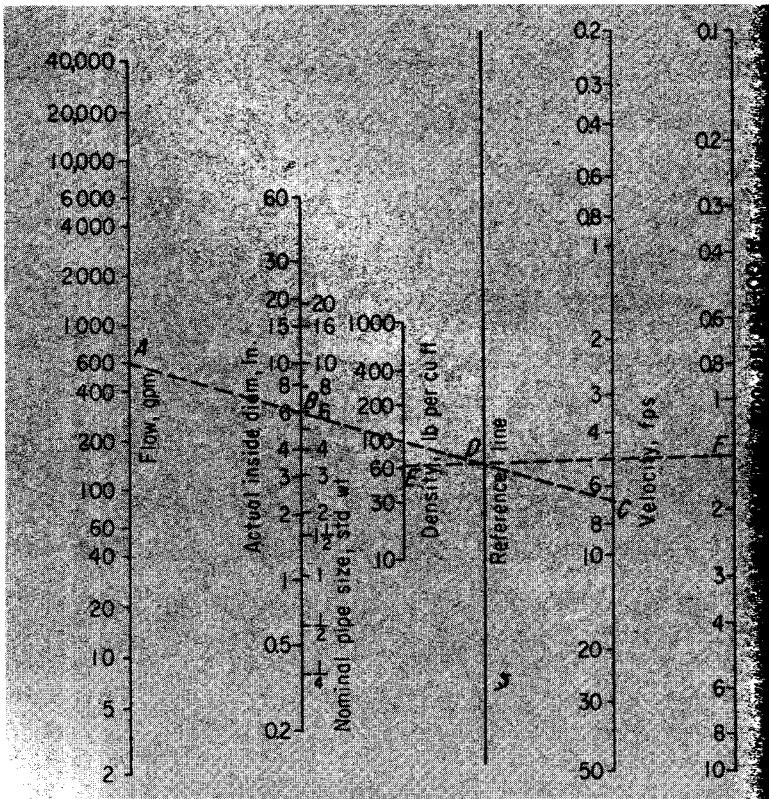
To find pressure drop for liquids, use the chart at top right. For example, a new 6-in. Schedule-40 steel line carries 600 gpm of water at 150 F. Flow velocity and pressure drop will now be calculated.

For a quick estimate using the nomograph, connect 600 gpm on the flow scale (A) with 6 in. on the actual inside diameter scale (B). Extend the line to the velocity scale (C); the velocity is 6.7 ft/sec. The extended line cuts the reference line at D; a line through D and E at 61.2 (150-deg water weighs 61.2 lb/cu ft) on the density scale is then extended to F on the unit pressure-drop scale. The value is 1.4 psi per 100 ft and if the line has the 94-ft equivalent length, as shown on page S-13, total pressure drop is about 1.3 psi.

For a more accurate solution, use the correction charts below the nomograph. In the lower chart, connect 600 gpm on the flow scale (G) with 6 in. on the nominal pipe-size scale (H). The line intercepts reference line 1 at J. Next, enter the temperature scale (at the left of the viscosity chart) at 150 F (K); move to the right, horizontally, to the line for water (L) and then straight down to reference line 2 (M). Connect points M and J and extend the line to reference line 3 in the bottom chart (N). Project down from N to the line for ordinary clean steel pipe (P), and then horizontally, to the correction factor at R: 0.73.

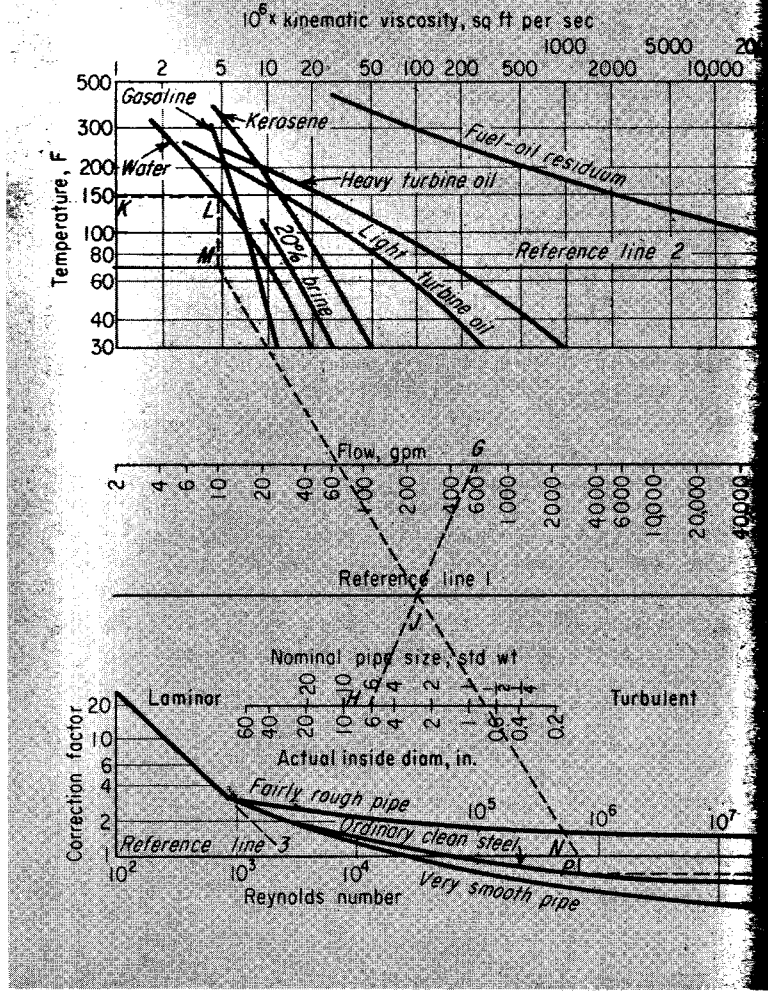
The corrected pressure drop is 1.3 x 0.73 or 0.95 psi for the 94-ft equivalent length.

In water piping, interior surface condition is important. At times, the friction factor plays a big-




**Pressure drop** for liquids hinges on flow, velocity, pipe size. This nomograph can be used to get a rough estimate for preliminary work

**Correction factor** for liquids allows designer to take temperature, visco and pipe-wall roughness into account to get a more accurate pressure



# give quick check of velocity and pressure drop values

ger part than the inside diameter value. If a smooth lining, such as cement or plastic, is put into a steel pipe handling mildly corrosive water, the result is often a net gain in pumping costs. Although the lining reduces pipe diameter slightly, it prevents future rusting and tuberculation that would greatly increase the friction coefficient.

Height difference is another factor in pressure-drop calculation for liquid flow. The difference in height between beginning and end of the piping line must be added as a plus or minus figure to the above-determined pressure drop.

### Steam and gases

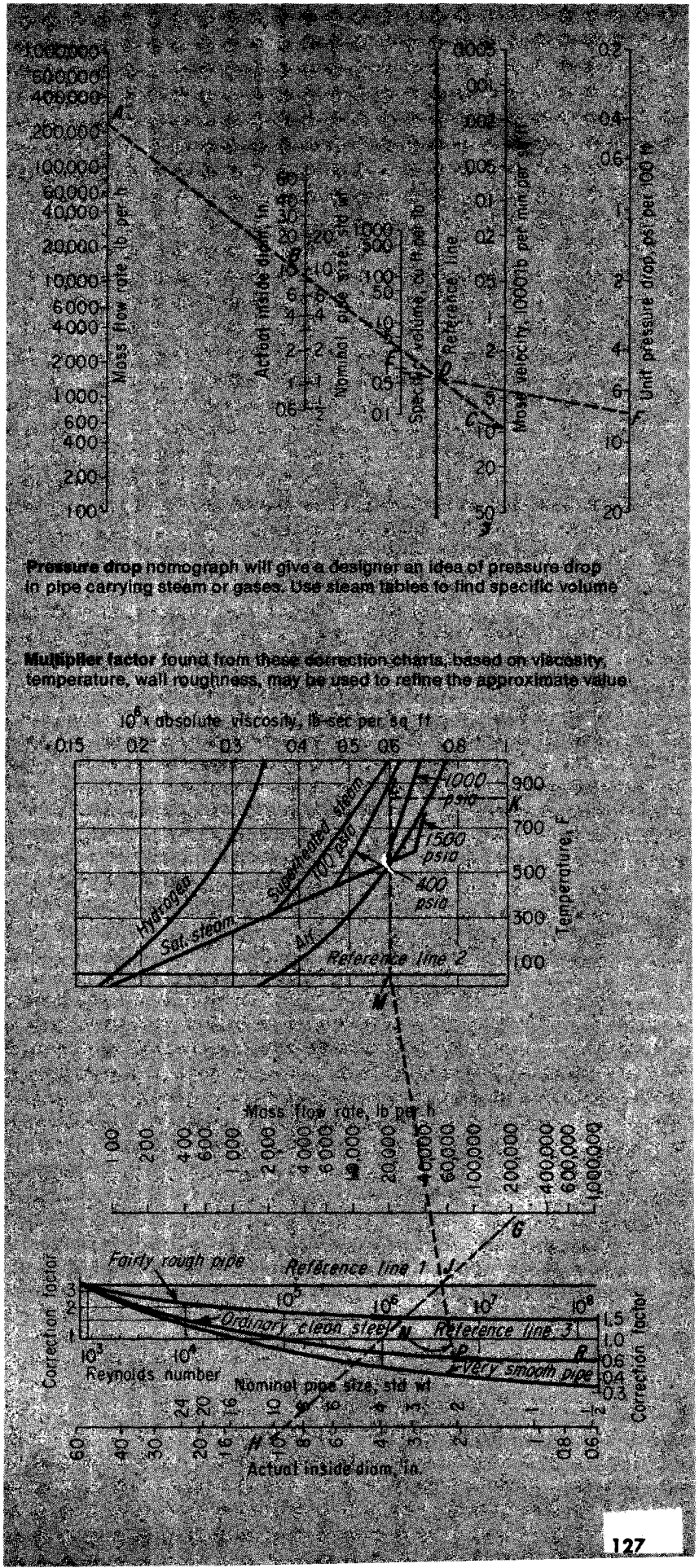
Charts on this page give unit pressure drop for steam and gas flow. As an example, assume that 250,000 lb/h of steam at 635 psig and 850 F flows through a 10-in. Schedule-80 pipe. The velocity and pressure drop per 100 ft must be found.

First find the steam's specific volume from steam tables: 1.153 cu ft/lb. Connect 250,000 lb/h (A) on the mass-flow rate scale with 9.56 in. (B) on the actual inside-diameter chart. (A 10-in. Schedule-80 pipe is 9.56 in. inside diameter.) Extend the straight line to C on the mass velocity scale and read 8300 x 1.153 = 9550 ft/min. Next, connect the reference-line intercept (D) of the A to C line to the 1.153 value on the specific-volume line (E) and extend the E-D line to F on the unit pressure-drop line. The value at F is 7.2 psi per 100 ft.

For a more accurate solution, the designer can use the two lower charts to obtain a correction factor. Draw a line from 250,000 lb/h at G on the mass-flow rate scale above the lower chart to 9.56 in. at H on the actual inside-diameter scale at the bottom. This line will intercept reference line 1 at J. Next, enter the temperature scale at the right of the viscosity chart at 850 F (K) and move horizontally to the estimated position (L) of 635 psig between the 400-psia and 1000-psia lines for superheated steam. Drop vertically down to reference line 2 (M). Connect M and J and extend the straight line to N on reference line 3 in the lower chart. From N drop vertically to P, on the line for ordinary clean steel pipe and then go horizontally right to the correction factor of 0.62 at R. The corrected drop is 7.2 x 0.62 or 4.5 psi per 100 ft.

Determine the pressure drop for air and other gases in the same way. Before solving pressure drop for gases other than steam, air and hydrogen, plot temperature vs viscosity on the chart.

Unlike liquids, steam and gases expand as pressure drops; this causes conditions in a long, high-pressure-drop line to change considerably from beginning to end. There are two simple ways to account for this and achieve a more accurate result. The first method uses an assumed average value for specific volume; trial and error provides a quick answer. In the other method, the long line is divided into two or more sections and an average specific-volume value is assumed for each.


Mass flow rate, lb per hr
Actual inside diam, in
Nominal pipe size, std wt
Specific volume, cu ft per lb
Reference line
Mass velocity, 1000 lb per min per sq ft
Unit pressure drop, psi per 100 ft
Pressure drop nomograph will give a designer an idea of pressure drop in pipe carrying steam or gases. Use steam tables to find specific volume
Multiplier factor found from these correction charts, based on viscosity, temperature, wall roughness, may be used to refine the approximate value
10^6 x absolute viscosity, lb-sec per sq ft
1000 psia
1500 psia
400 psia
Superheated steam
Hydrogen
Sat. steam
Air
Reference line 2
Temperature, F
Mass flow rate, lb per h
Fairly rough pipe
Reference line 1
Ordinary clean steel
Reference line 3
Very smooth pipe
Reynolds number
Nominal pipe size, std wt
Actual inside diam, in
Correction factor
Correction factor

# Selection of materials and pipe quality, next step in system

After calculating the internal diameter needed for piping in a line, the designer must select materials and consider their strength. The factors influencing choice of materials are temperature, pressure, corrosion by fluid, atmospheric corrosion, shock, water hammer, fire resistance and thermal expansion. Choice of material is simple if previous experience proves that one material works best in a given application. Occasionally, however, a job requires a full-scale engineering and cost study. Designers must compare the total lifetime cost of piping systems using competing materials; they cannot merely consider the cost per foot of pipe from the warehouse.

**Stress calculation** is necessary for more exacting work, and starts with the basic hoop stress in the pipe wall, as shown below, left. This stress calculation ignores longitudinal wall stress that exists if the pipe has closed ends. An example of this is a flask or short header. The closed-end effect is often absent in actual piping, so it is best not to count on its effects. The piping codes do not.

Advanced analysis shows that for thin-wall pipe, the outside diameter should be used in the hoop stress equation:

$$S=\frac{P\,D_o}{2t},$$

with $D_o$ as the outside diameter. This equation, called the Barlow formula, is the basis for most code stress calculation. The formula is good for thick-wall pipe, too.

The allowable stress in a pipe wall is not determined solely by the material's strength at the service temperature. In pipe with a longitudinal welded seam, the efficiency of the welded joint must also be considered. Code section B31.1, for power piping, gives efficiency factors of 0.60 for a furnace butt weld, 0.85 for an electric resistance weld, and 1.00 for single or double butt weld with 100% radiography. Allowable stress is calculated by multiplying the value for seamless metal at the given temperature by efficiency factor. Tables of allowable stress in codes, such as B31.1, take joint efficiency into account for welded pipe.

Code section B31.1 adds factors to the Barlow formula:

$$t_m=\frac{P\,D_o}{2(S+Py)}+A$$

is an equation for determining the minimum wall thickness needed to resist internal pressure. The factor y can be obtained from the table:

| | Temperature, F | | | | | |
|---|---|---|---|---|---|---|
| | to 900 | 950 | 1000 | 1050 | 1100 | 1150 and up |
| Ferritic steels | 0.4 | 0.5 | 0.7 | 0.7 | 0.7 | 0.7 |
| Austenitic steels | 0.4 | 0.4 | 0.4 | 0.4 | 0.5 | 0.7 |

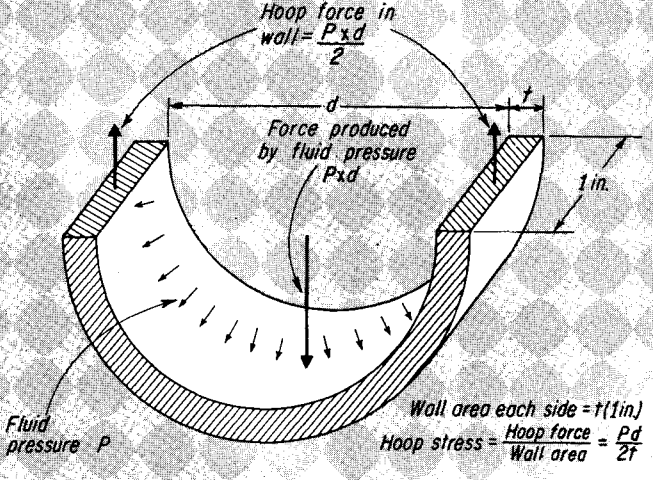
The quantity A, an added thickness for threading or grooving and giving mechanical strength to the pipe, ranges from about 1/16 to about 3/16 in.

In calculating value of P (internal pressure) it may be necessary to include additions to the normal line pressure—allowance for water hammer and for pressure surges.

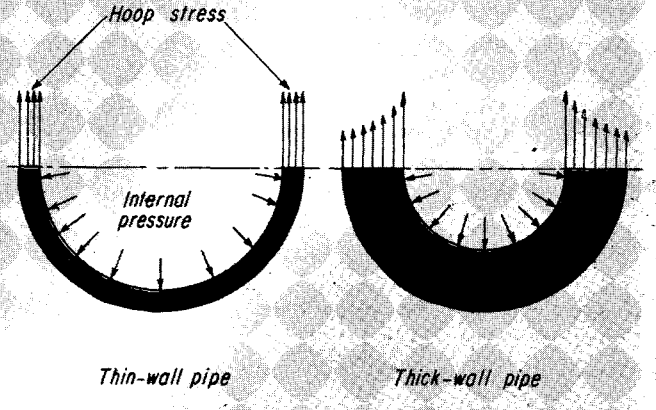
The value of S (allowable stress) is determined for ferrous materials below the creep range by the B31.1 code section as the lowest of either 25% of minimum room-temperature tensile strength, 25% of minimum tensile strength at operating temperature, or 62½% of minimum yield strength for 0.2% offset at operating temperature. Other B31 code sections determine allowable S values in a slightly different manner: B31.7, for nuclear power piping, represents code writers' latest thinking on this subject.

B31.1's allowable stress for nonferrous metals is the lower of 25% of minimum tensile strength or 66⅔% of minimum yield strength. Creep figures here, too.

The piping designer must consider additional factors, as shown in the upper figure, right. Corrosion and erosion may necessitate added material. Bending to small radii thins the outer wall at the bend, and pipe selected must allow for this. Inside diameters of pipe to be welded to-


Hoop force in wall = P x d / 2
d
t
Force produced by fluid pressure P x d
1 in.
Fluid pressure P
Wall area each side = t(1 in.)
Hoop stress = Hoop force / Wall area = Pd / 2t

**Pipe's most critical load** — the circumferential or hoop stress within pipe wall — results from pressure built up by the fluid




**Most piping** for general service is in thin-wall stress class. Higher pressures, now more common, require use of thick wall

# design, calls for the use of practical wall-strength checks

gether may not match closely enough at the joint, and, as a result, the pipe ends may have to be bored out; this requires a weld-fitup allowance.

**High-temperature piping** must be analyzed for flexibility to insure that thermal expansion, acting simultaneously with fluid pressure, does not overstress the pipe. According to the B31.1 code section, the expansion stress must not exceed an allowable stress range. This range depends on the pipe material's allowable stress at cold temperature, at hot temperature and the number of full temperature cycles that the piping will encounter in its lifetime. The basic idea behind the stress-range concept is this: although the hot-temperature stress will tend to be reduced by creep effect, the hot elongated pipe will contract when it cools again, and the total range of stress will therefore stay constant.

Complete analysis is usually complicated and laborious, so many shortcuts and approximations have been developed. Today, electronic computers are a great help.

After selection of a desired minimum wall thickness, choice is usually made from standard weights or schedules. Originally, manufacturers tried to give all pipe sizes in a given schedule the same pressure rating (such as in Schedule 40, formerly called standard). To accomplish this, the wall of smaller pipe sizes was made extra thick. Advances in manufacturing have improved small-size pipe so that in the present schedule system the smaller sizes are rated for higher pressures than are the larger sizes.

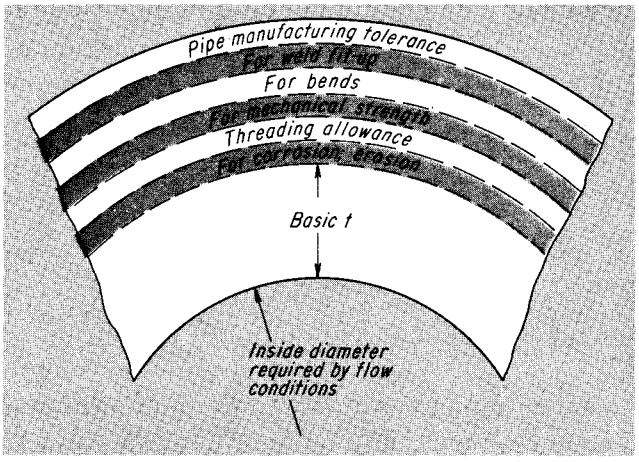
When plastic piping appeared, the manufacturers made plastic pipe according to older schedules, such as 40 and 80, but also introduced a new dimension system called the SDR (standard dimension ratio). All pipe sizes of a given SDR number have the same ratio of outside diameter to wall thickness and therefore are all rated for the same pressure. This type of thermoplastic pipe has thin walls in small sizes and is joined preferably by methods that do not cut into the wall. Illustration, lower right, compares Schedule 80 and SDR PVC pipe.

ASTM specifications are the most important ones for energy-systems piping. Several of the commonly used specs are described here.

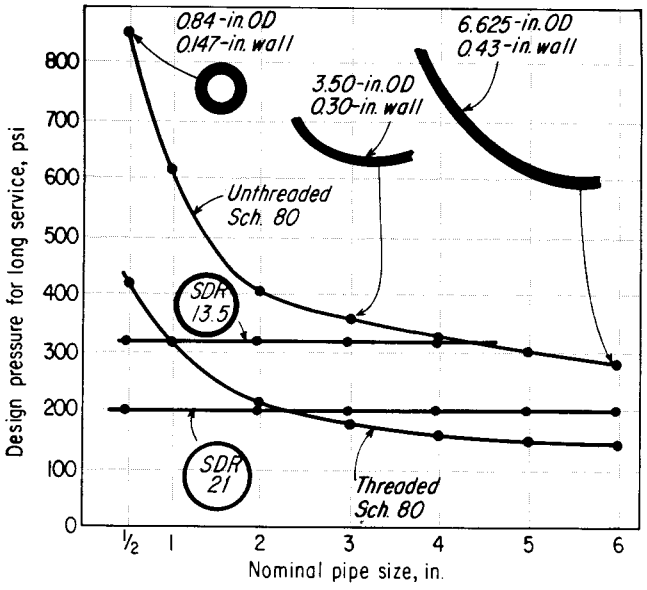
**ASTM A120-68a,** welded and seamless steel pipe for general use, covers a pipe that meets minimum requirements and is intended for all common fluids at moderate temperatures; code section B31.1 allows 5700 psi stress at 450 F on butt-welded A120, and 9600 psi on the seamless variety. Each length gets a short hydrostatic test for a tangible assurance of quality, but no minimum tensile strength or yield strength is required and no flattening test is specified. Wall thickness can go as high as 12½% below nominal and the outside diameter can vary 1% each way for sizes 2-in. and over; these factors are significant for careful calculation.

**ASTM A53-68,** welded and seamless steel pipe, represents a higher step towards quality. This pipe is subject to modest chemical limitations, its metal must meet tension-test requirements and the finished pipe receives bending or flattening tests in addition to the hydrostatic test.

There are three types of A53 pipe — furnace butt welded,



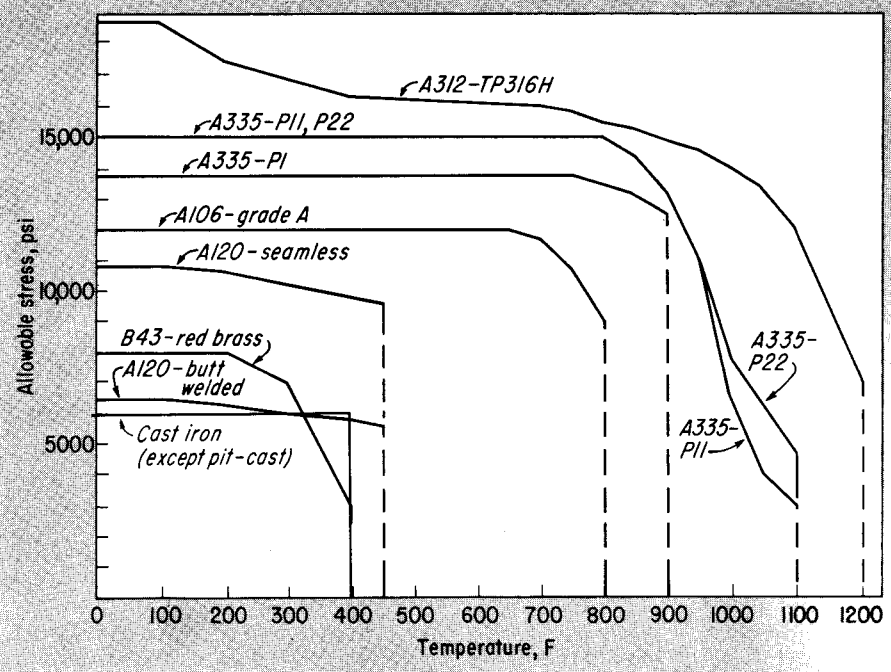

**Wall thickness** is determined by factors shown above, in addition to stress resulting from fluid pressure. Equations as outlined in code sections take some of these into consideration




**Standard ratio** of diameter-to-thickness for PVC plastic pipe, termed SDR, allows all sizes to withstand the same pressure

electric resistance welded and seamless; the latter two can be in Grade A or B. The furnace butt welded type is not recommended for flanging. Except for this limitation, A53 is suitable for welding and for some forming if not severe. Grade A is lower in strength (48,000 psi) and higher in elongation (28% for a standard specimen) than is Grade B (60,000 psi and 22%), so if a designer expects the pipe to be close coiled or bent cold, he should specify Grade A. The figures at the lower right on p. S-19 illustrate tests for bending and close coiling. For sizes over 2 in., a flattening test, shown at upper right on p. S-19, is used.

Limitation of phosphorus is another safeguard to the pipe's quality. Depending on the steelmaking process and




**B31.1 code section gives wide selection of metal pipe**

**This chart shows allowed stress for various pipe choices listed in B31.1. Creep and other effects limit upper temperature on all these pipes.**

**Cast iron is still acceptable for saturated steam service to 250 psi. Red brass's rapid loss of strength is typical of many copper alloys. The effect of weld-joint efficiency factor is obvious when A120 seamless is compared with A120 butt welded. A106 pipe contains a higher-quality steel than does A120, so the code assigns it both higher stress value and higher temperature limit, 800 F in this case. Carbon-moly and chrome-moly alloys (A335 P1, P11, P22) are higher in strength and temperature rating; the austenitics, such as A312, are rated highest, with a limit of 1200 F, adequate for current central-station practice. Code section B31.1 gives wide enough choice in pipe to meet most needs.**

spec type, the maximum ranges from .048% to .13%.

All in all, A53 is a good pipe for moderate steam service; B31.1 allows seamless A53 to be used up to 800 F (p. S-7).

Three related types of large welded pipe will be examined next. Two are chiefly for fluids other than steam and one is solely for steam.

**ASTM A135-68a,** electric-resistance-welded steel pipe, up to 30 in. diam, for liquid, gas and vapor, is made in two grades. Grade A has lower tensile strength (48,000 psi) and higher elongation (35%) than Grade B (60,000 psi and 30%) and is suitable for flanging and bending.

This pipe's metal has a sulfur limit of .06% in addition to a phosphorus limit (.05%).

Tension test, flattening test and hydrostatic pressure test are required. The latter test calls for pressure that develops 16,000 to 18,000 psi hoop stress by the simple Barlow equation (for Grade A) and 20,000 to 22,000 psi for Grade B. For small, very thin-wall A135 pipe (¾ to 5-in. size in Schedule 10), other nondestructive tests can be administered as an alternative to the hydrostatic test.

The wall thickness can be 12½% below nominal and outside diameter can vary up to 1% high or low.

**ASTM A134-68,** electric fusion (arc) welded steel-plate pipe 16-in. OD and over, is intended for the same type of service as A135, but now, for the first time in our series, the specification requires that material meet an ASTM specification for plate.

Welding procedure must be qualified. Tension tests made on weld specimens with weld reinforcement removed must show tensile strength equal to the minimum specified tensile strength of the base metal. A bending test is required, too; excessive cracking results in rejection.

Hydrostatic test holds the pipe for 5 sec at 60% of yield point; the pressure for this is calculated from the basic Barlow formula, using specified thickness and outside diameter. In this test, as in hydrostatic tests for other ASTM pipe, the pipe under test is struck by a 2-lb hammer near the weld at both ends of the pipe length. The purpose of these hammer blows is to release latent weld defects that withstand steady internal pressure for a short time. The hammer is not used on lighter wall pipe, 0.154 in. or less.

There are no specifications concerning wall-thickness tolerance for A134; this is inferred in plate specifications. No outside-diameter tolerance is given, either; instead, a circumference tolerance of ±1% is specified. Out-of-roundness is not mentioned. These broad tolerances hamper critical stress calculation.

**ASTM A155-68a,** electric fusion-welded steel pipe for high-pressure service, resembles A134 but is subject to tighter requirements. A155 calls for ASTM steel plate and in certain types — A515 and 516 — the plate steel must be "killed." The upper left figure, p S-19, illustrates the difference between "killed" and "rimmed" steel.

A155 is the first pipe in our series that can be made of several low-alloy steels, as well as carbon steel.

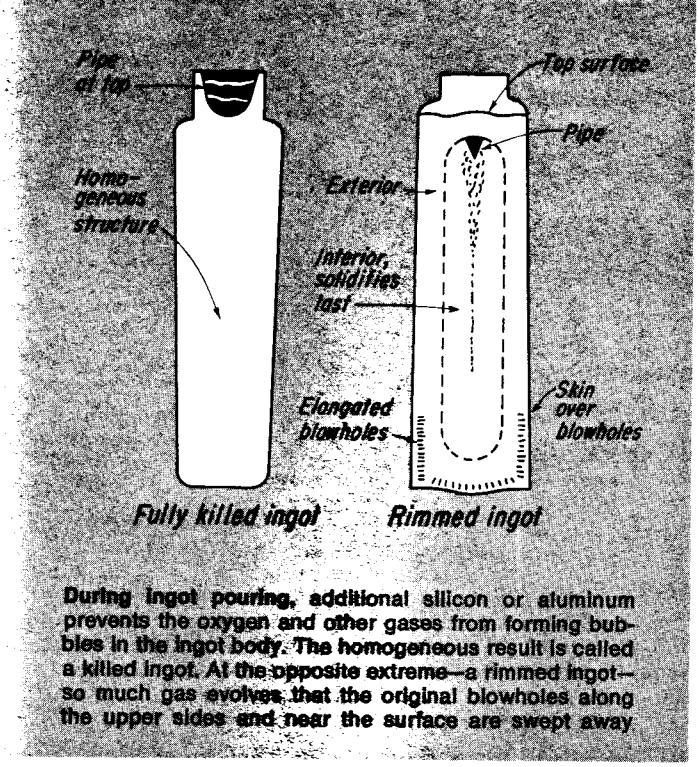
ASTM specs for the initial carbon-steel plate for A155 pipe require flange or firebox quality of A285; compared to A134 pipe, requirements are far tighter.

Heat treatment is a must for all Class 1 A155 pipe and for most Class-2 pipe. The treatment is conducted at 1100-1250F; again, quality improves, compared to A134.

A155 pipe is intended for h-p h-t service; wall-thickness calculation can become critical. Requirements for thickness tolerance must be far tighter than for A134 pipe or general-service pipe. The thickness tolerance is only .01 in. below nominal thickness for both carbon and alloy-steel varieties. Circumference tolerance is ±½%.

In the seamless-pipe field, there are several higher-quality types commonly used.

**ASTM A106-68,** seamless carbon-steel pipe for high-temperature service, is rated by B31.1 for temperatures up to 800 F. This pipe can be bent and flanged. The material must be "killed" steel made by open hearth, basic oxygen, or electric-furnace process. In all but the smallest sizes, the




**During ingot pouring, additional silicon or aluminum prevents the oxygen and other gases from forming bubbles in the ingot body. The homogeneous result is called a killed ingot. At the opposite extreme—a rimmed ingot—so much gas evolves that the original blowholes along the upper sides and near the surface are swept away**

pipe must be hot finished: this eliminates any strengthening or hardening effect from cold work.

A106 must meet chemical requirements; carbon, manganese, phosphorus, sulfur and silicon content have maximum limits. Three grades — A, B and C — are available. Grade C, with 70,000-psi tensile strength, is furnished by special agreement only. Tests for A106 include a tension test and, on pipe over 2-in. in size, a flattening test is required. Bending is tested only on very small pipe and on a specimen from large-diameter heavy-wall sizes. Of course, hydrostatic pressure tests are made. This specification adds supplementary requirements for pipe 8-in. or bigger, operating at 400 psi and above in central stations.

**ASTM A335-65,** seamless ferritic-alloy steel pipe for high-temperature service, is higher in quality. This pipe, made of carbon-moly or chrome-moly steel, is used at temperatures up to about 1000 F. Code B31.1 permits the use of some A335 at 1200 F, but allowable stress there is very low — 1200 to 1500 psi. A335 pipe receives tension, flattening and hydrostatic tests.

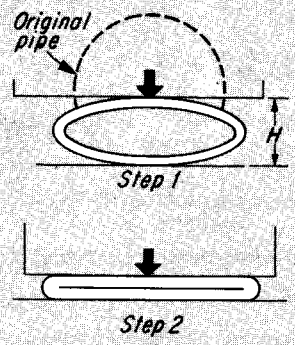
Because the wall thickness can vary by 12½% below nominal, it is sometimes advisable to use ASTM A369 pipe, which is similar to A335, but is forged and bored for closer tolerance — nominal thickness to an extra ⅛ in.

ASTM A358-65, A312-64 and A376-64 pipe, made of austenitic stainless steel, are rated by B31.1 for temperatures to 1200 F, where some grades carry allowable stresses as high as 6950 psi.

A358 pipe is welded, A312 can be either welded or seamless, and A376 is seamless. A358 pipe has a thickness tolerance of only .01 in. below nominal; because this pipe is made of plate, the tolerance can be lower than the 12½% under-thickness tolerance of the other two specifications.

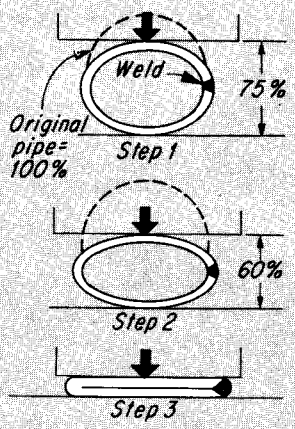
There are many other important points in ASTM specifications for energy-systems pipe. ASTM specs and those of other agencies such as the AWWA, cover steel pipe as well as other materials for pipe serving varied purposes.

## ASTM tests check soundness and formability




**Seamless flattening test**

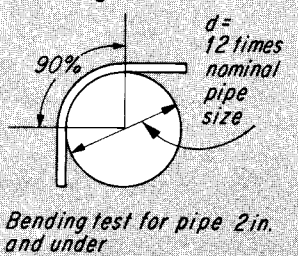
Seamless pipe's cold-flattening test is a two-step process. In the first step, the short specimen of pipe is squeezed to height H, which depends on pipe size, wall thickness and material. This step tests ductility. In step 2, pipe is compressed until it breaks or until walls touch, testing soundness.



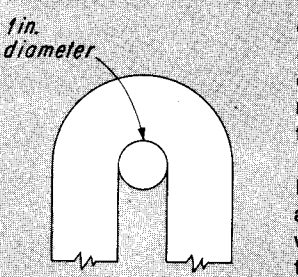

**3-step welded-pipe test**

This tests butt-welded Schedule 40 and 80 A53 pipe over 2-in. in nominal size. First step checks specimen's weld quality to 75% of original OD; no cracks or breaks on inside, outside, or end surfaces. Step 2 tests ductility of metal other than the weld. In Step 3, compression continues until pipe breaks or walls touch; this step tests soundness, as in seamless test above.

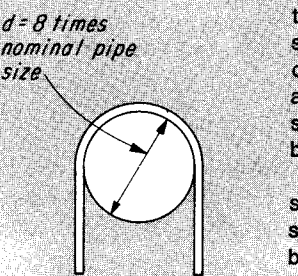
### Bending tests determine important property of pipe




Bending test for pipe 2 in. and under




Bending test for large, heavy-wall pipe (over 25 in. diam)




Close coiling test for small pipe

These bending tests for ASTM steel pipe illustrate how simple experience-based tests can tell designers whether a material will be suitable for the desired purpose. The bending test shown at top, is performed cold on pipe 2-in. in size or less and indicates whether or not the pipe can be bent during installation or fabrication. The test piece must not fracture or crack during the entire test.

The second test is for large heavy-wall pipe, such as A106 of 25-in. or larger with a ratio of OD to wall thickness of 7 or less. A bend-test specimen is cut from the pipe and cold-bent as shown; to pass the test, the specimen must not crack seriously. This test is adequate for determining formability of the large pipe itself. Usually, large pipe is bent or formed hot.

The close-coiling test, shown at bottom, is more severe than the ordinary bending test. If pipe is to be close-coiled, requirements and proper grade must be indicated in the order.

# JOINING PIPING

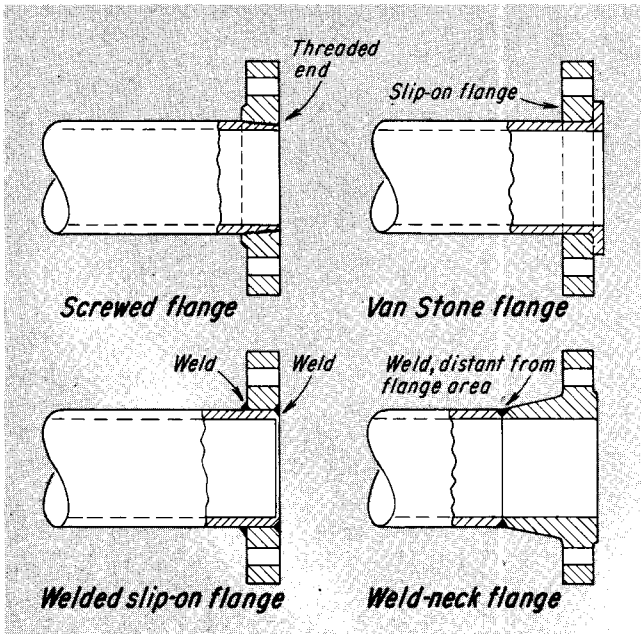
**For metals, mechanical joining and welding are methods used, while the plastics depend on adhesives, as well. Heat treatment along with nondestructive testing are proving important for all code work**

Joining lengths of ferrous pipe in the field requires use of a mechanical assembly or thermal welding. Either mechanical methods or brazing is used for nonferrous metals. Brazing calls for a metal that melts at a lower temperature than the pipe and adheres to the pipe metal on cooling. Plastics employ mechanical joining, thermal and solvent welding, in effect, adhesion.

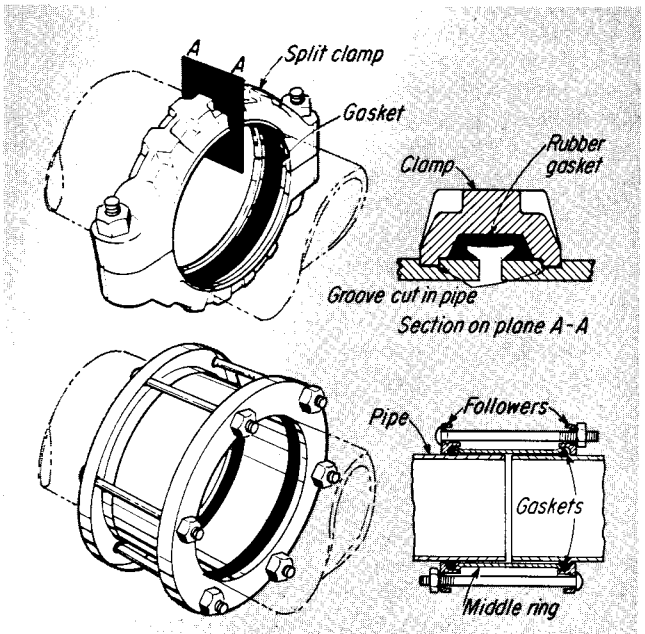
**The mechanical methods** allow for easy assembly and disassembly. Simplest is the taper-pipe thread used at low pressures, moderate temperatures and for pipe sizes to about 6 in. Welding may be used to seal screwed joints. The new code section, B31.7, for nuclear power piping, does not rule out screwed joints but does require a sealing medium such as a seal weld.

The flanged joint can be used at high pressures and temperatures, but it tends to leak in such ranges; repeated welding and cutting is sometimes a preferred choice. Usually, screwed flanges are the least desirable. Lapped (Van Stone) flanges are made by flanging the pipe end itself; the flat-lapped faces are drawn together by bolts in loose slip-on flanges. In the weld-neck flange, the material near the flange can be as heavy as desired and the neck can taper almost to pipe-wall thickness. The weld is at a distance from the flange itself, so that welding heat has little effect on the flange. Cast-iron pipe often has integral flanges. In flanged joints, sealing against leakage can be accomplished either by lapping the metal faces or by using compressible gasket material. Creep at high temperatures poses a problem for flanges and their gaskets. Distortion acceptable in the pipe itself causes a flanged joint to leak. Chief drawback of flanged joints is leakage rather than lack of strength.

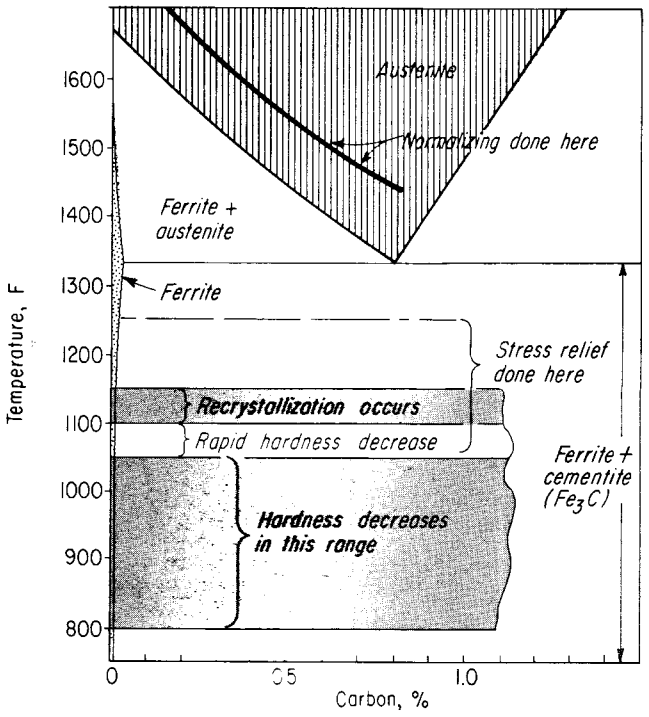
Several couplings that use rubber or plastic gasket seals are available for metal piping operating at room temperature or slightly above. Two of these are shown below. The groove type resists axial pull. The compression-sleeve type needs an external axial restraint; this requirement is not a serious drawback for many kinds of piping. A new compression-type coupling produces axial restraint through the friction that is developed by tightening sliding flanges together over tapered-surface sleeves. The sleeves grip the outer surface of the pipe, compressing the seal ring between them and sealing the pipe joint. This type of coupling can be used on thin-wall pipe. Through improvements in sealing materials, the temperature range of these coup-




**Flange designs** vary widely. Screw type, the simplest, serves low pressures; weld-neck suited for high pressure




**Groove-type coupling** (upper) withstands high axial load; compression-sleeve design (lower) handles gas, liquids




## Pipe heat treatment helps maintain ductility

The diagram at left is an enlargement of part of the carbon-steel phase diagram shown on p. S-7. In carbon-steel pipe, heat treatment is rarely used for improving strength or hardness of the metal. Because of the low carbon content in pipe steel, a quenching type of heat treatment from temperatures in the austenite region is not effective. In addition, if a hardened carbon steel is welded, welding heat removes the effect of the heat treatment near the weld. Code section B31.1 gives no credit for most special heat treatment.

Normalizing, stress relief and preheating for welding are the most important heat treatments for carbon-steel pipe. In normalizing, the steel is heated to about 100 F inside the austenite region and then air cooled. This treatment gives improved grain size and homogenizes the grains. Air-cooling is fast enough to prevent harmful changes in grain size but not fast enough to change the austenite into hard martensite. At normalizing temperature, the steel is soft enough to cause complicated bulky weldments or long pipe pieces to distort under their own weight. If dimensions are critical, careful preparation for support in the furnace must be made.

In stress relief, the pipe is heated to the range shown and the heat causes release of internal stresses from cold work or from other sources. Carbon-steel pipe is stress-relieved after welding only when wall thickness exceeds ¾ in.

lings could be extended to 500 F, in the near future.

The bell-and-spigot type coupling and its close relative, the solvent-weld coupling for plastic pipe, make use of an old idea. Recently, the bell-and-spigot has been used with plastic or rubber gasket ring for plastic pipe and for asbestos-cement pipe carrying a plastic covering on the end. The annular gasket ring, mounted in the bell, seals against the outside of the spigot end.

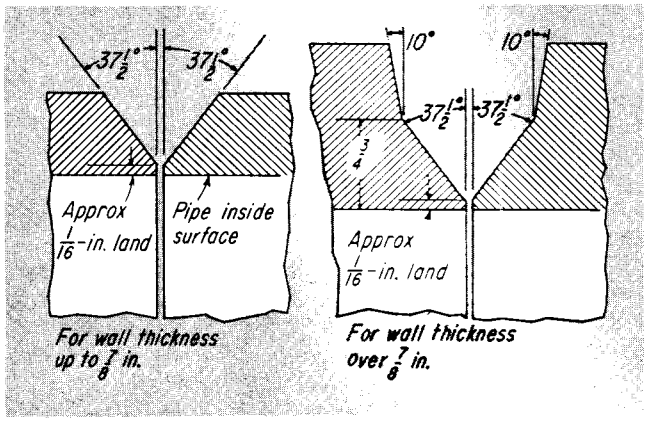
Before reviewing welding techniques, mechanics of heat treating must be examined. Diagram and box copy above cover some methods of heat treatment for carbon steel. Alloy-steel welding involves several other treatments.

Some grades of welded austenitic stainless experience chromium-carbide precipitation at grain boundaries during cooling. Chromium comes from nearby metal — result may be corrosion. Restoration requires heat treatment at about 2000 F, followed by a water quench. In power piping, this kind of corrosion is generally not serious and the restoration technique is seldom used. Instead, stabilized or extra low-carbon stainless grades see service.

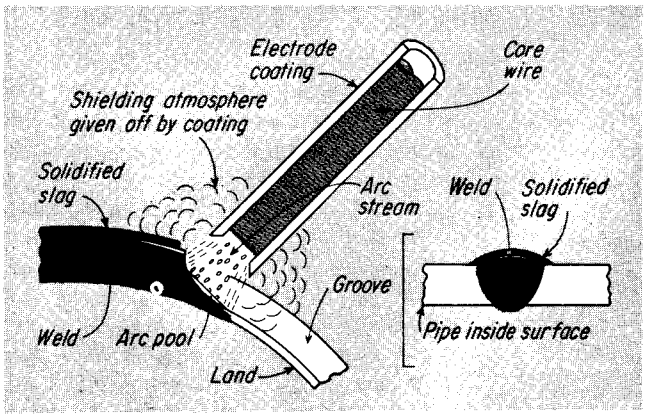
Welding is the only large-scale joining method for h-p h-t piping and is widely used for all types of steel piping. The circumferential butt weld predominates, but some fillet welding is done on socket fittings. In welding processes for joining steel piping, the pipe metal at the weld joint is brought to melting point by the heat of an electric arc and is fused, usually with addition of other metal. Sometimes, small pipe is furnace butt welded longitudinally. Melting does not occur here; the soft hot metal is fused under pressure. Because the metal in a weld goes through all temperatures — from room temperature to melting and back again — a designer should know the metal's high-temperature phases and metallurgy, too.

Pipe welding is done with the arc and molten-metal

## Pipe-end preparation is important step prior to the field welding of common steel piping

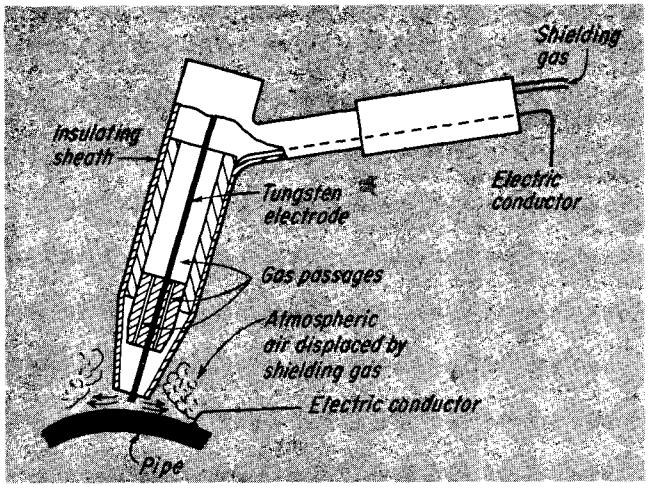


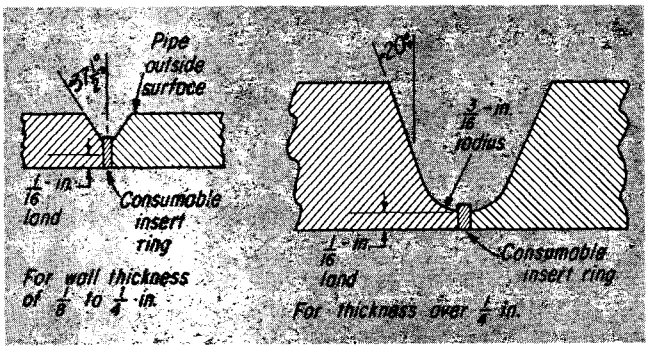

**Beveling** of pipe ends is first move in preparing for most welds. Thin walls (below 3/16-in.) need only square cut




**Shielded-arc electrodes** have a protective coating. Use of low-hydrogen electrodes aids in improving the weld

# Much critical piping is welded by gas tungsten-arc (TIG),





Pipe outside surface
Consumable insert ring
For wall thickness of 1/8 to 1/4 in.
3/16 in. radius
1/16 in. land
Consumable insert ring
For thickness over 1/4 in.

**TIG welding process** makes the vital first-pass weld. The arc goes from the durable tungsten to the pipe metal at root of the weld-joint preparation, shown in illustration, above. Consumable insert ring, sometimes set slightly off center, helps obtain crackfree root pass that is so essential in high-grade welds

zone shielded from the atmosphere by inert gases or by flux, a fine-grained mineral material that covers the weld zone and solidifies over the completed weld metal.

The lower right figure on p. S-21 illustrates the most common pipe-welding method — shielded metal-arc welding. The electric arc formed between the welding electrode and the pipe metal heats the pipe metal and melts the electrode end; electrode metal is transferred to the arc pool. In this process, the electrode coating has two functions: it supplies inert shielding gas to keep air away from the molten metal, and it provides a flux for a protective slag over the cooling weld metal. Shielded metal-arc welding is performed manually. Complete removal of slag between passes is important. The simple preparation of the pipe end for this process is shown in the lower left figure, p. S-21. On heavy-wall pipe the bevel is steeper at the top; this reduces the required amount of filler metal. Either machining, grinding, or oxygen cutting can prepare the pipe end.

Sometimes backing rings are used inside carbon-steel pipe. These machined rings straddle the joint and fit against the pipe wall, which can be machined if necessary.

Another welding process often used for critical power piping, especially h-p h-t piping, is the inert-gas tungsten-arc (TIG) process, with consumable insert ring. This type of ring gives a smoother interior contour at the joint and makes radiograph interpretation easier. The ring takes the place of a separate metal wire and is easier to use than the separate wire. The TIG process is shown above.

After the root pass has been made and inspected, the rest of the groove must be filled. The TIG process is not as suitable for this as other methods because it is too slow. In its place, the MIG (inert-gas metal-arc) process finds use. The upper left figure on facing page outlines the method: a wire, fed mechanically into the arc between wire end and pipe metal, melts and remains in the joint. Inert gas shields the molten zone from the surrounding air. The electric current passes though the wire, arc and pipe metal and goes back to the welding machine. Metal deposit from the power-fed wire is fast.

Another process, used on large pipe, is the submerged-arc process, in which uncoated electrode wire is deposited across an arc hidden under a measured feed of granular flux. This method will quickly deposit large quantities of metal. The root pass is often TIG-welded. In the submerged-arc process a large amount of heat is generated, giving deep fusion.

Chemistry of the weld metal can vary from chemistry of the pipe's metal, if desired. This is accomplished by adding alloying elements in either flux or electrode metal.

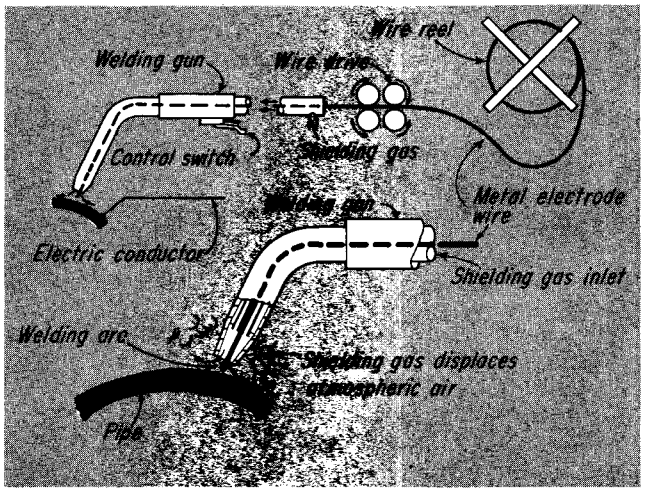
Qualification of welding procedures and welders is required in code work. For B31.1 and B31.7, the requirements are largely those given in Section IX of the ASME Boiler and Pressure Vessel Code. Development of welding procedure covers much more than mere selection of successive processes, filler rod and heat treatment. Exact details of joint preparation, movement and handling of the pipe, tack welding and clamping, welding currents, metal-deposit rates and inspection must be included.

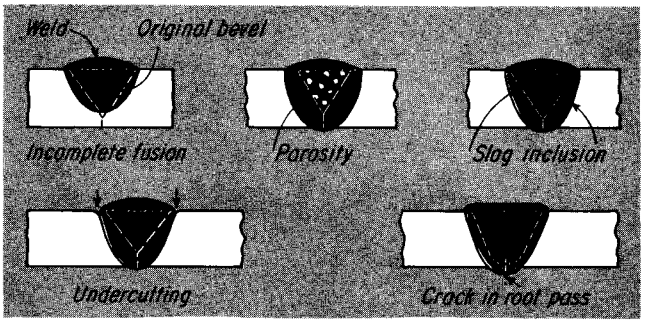
Perhaps the most serious disadvantage of welding as a pipe-joining method is the wide variety of defects that can occur, both obvious and hidden, unless quality control is constant and unremitting. The upper right figure on the next page shows some of these defects in the weld-fusion area. Other defects occur in nearby metal affected by welding heat — grain coarsening, hardening, carbide precipitation and cracking are among them.

How can inspectors find defects that occur even after quality control has been pushed to its practical limits? This problem exists at all stages of piping fabrication and the detection methods are the same for all stages.

For flaws that extend to the surface, the eye is good, but magnifying devices can aid the eye. Borescopes and liquid penetrant, a fluid that is drawn into fine cracks by capillarity, are both practical aids. The fluid, applied to the clean cool metal surface, contains either a bright red dye or a fluorescent dye. A quarter-hour or so after application the

# gas metal-arc (MIG), or submerged metal-arc methods




**Weld defects** resemble common defects in all cast metal. Crack may start from a concavity, here exemplified by undercutting

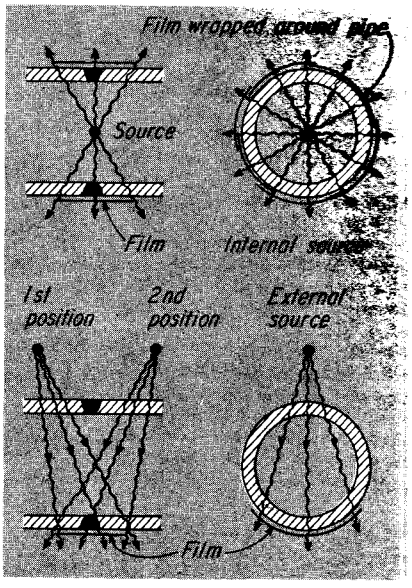
**MIG process** is automated to coordinate filler-wire feed with welding current. Metal deposits are faster than in TIG process

surface is wiped clean or rinsed off. Developer, sprayed on the metal, dries to a white film against which red dye, oozing out of the cracks, is plainly visible. Ultraviolet light reveals the fluorescent penetrant. Surfaces that are hot, rough, or contaminated make liquid-penetrant testing extremely difficult. Problems have occurred in nuclear piping when penetrant was allowed to remain in the cracks.

Magnetic-particle inspection is a method that detects surface cracks in ferromagnetic metal. A current, flowing between two prods at points on the steel's clean surface, produces a magnetic flux that attracts magnetic particles to discontinuities in the flux. In the dry method, generally used for piping, the particles are sprinkled on the surface and the excess is gently blown off, leaving only those particles attached to discontinuities. The dry method will reveal some subsurface flaws too, but inspectors rely more on radiography or ultrasonics for checks in the interior.

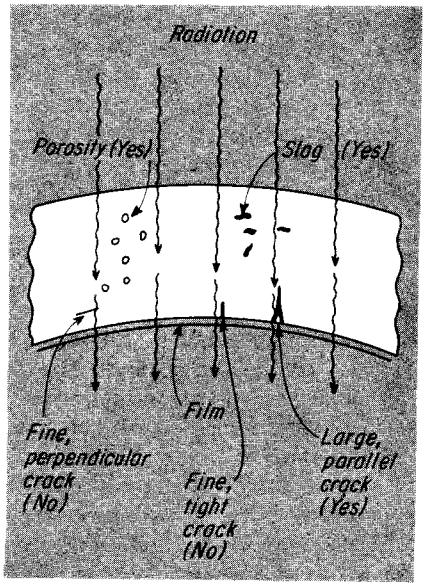
In radiography of piping, either tube-produced x-rays or radioisotope-generated gamma rays penetrate the pipe and strike a film exposed on the opposite side. The film record is permanent and available for reference years later. Main defects sought are porosity, slag, internal cracks and incomplete penetration. Sensitivity and interpretation are important factors in radiography of piping. Very small or thin defects, or those that pass as much radiation as the base metal, are not revealed; no contrasting shadow or bright spot appears. Defects that are easily visible do not always cause rejection. A certain amount of porosity or slag does not cause serious damage to the weld. All codes recognize this and have set up standards (a visual comparison type for porosity) based on experience.

The penetrameter assists the radiograph interpreter in

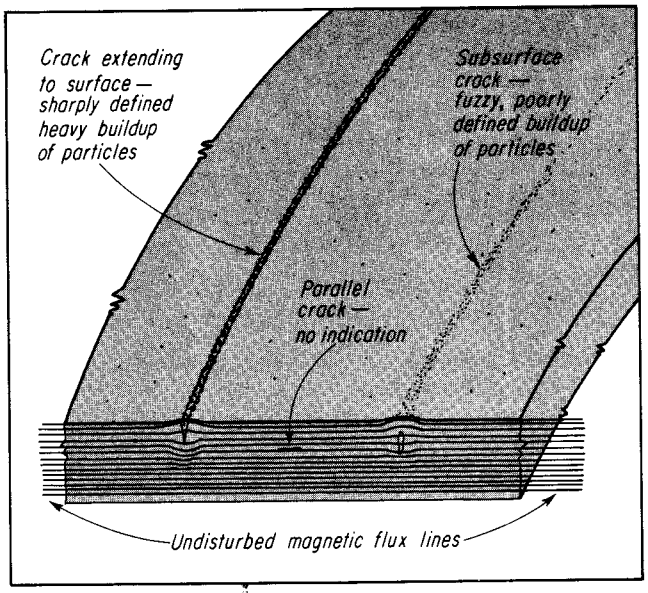



## Radiography requires careful planning, skilled interpreting

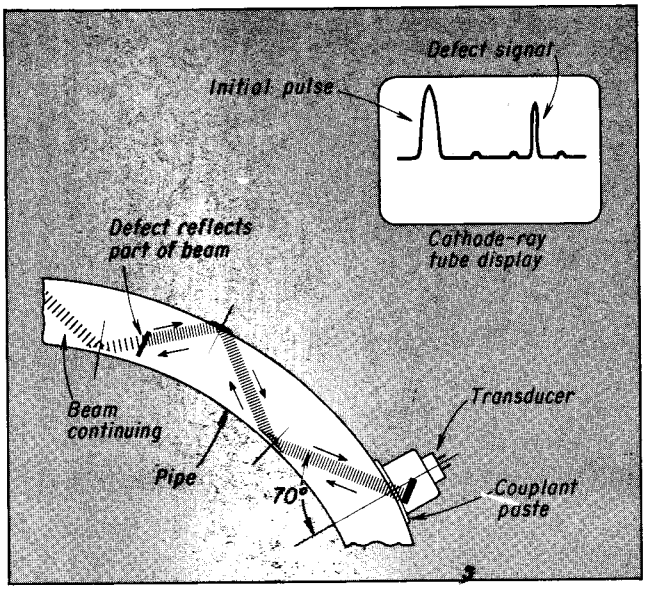
The figure at left shows two placement possibilities of radioactive source and film. Two source positions, with separate film exposed for each, may be needed to reveal defects unfavorably oriented. The radiographer must understand the welding process and know what defects are likely to occur and how they are oriented. The figure at right shows how defect orientation and size determine whether radiography can reveal the flaws. Remember, too, that a "Yes" only means that the defect can be detected if source strength and distance, film type, exposure time and inspector's skill are adequate. In heavier plate, defects 2% or more of metal thickness can be detected. Crack detection is sometimes difficult.



# Eddy current and ultrasonics test pipe nondestructively


Crack extending to surface — sharply defined heavy buildup of particles
Subsurface crack — fuzzy, poorly defined buildup of particles
Parallel crack — no indication
Undisturbed magnetic flux lines

**Magnetic particles** indicate irregularities in magnetic flux. Current between probes aligned parallel to flaws causes flux




**Ultrasonic transducer** sends sound beam through couplant paste and into pipe. Ultrasonics can find wall thickness, too

judging sensitivity; other picture evidence, however, is considered more reliable. A penetrameter is merely a thin plate, no more than 2% of the metal thickness; it is placed on the pipe-wall surface, preferably opposite the film and towards the source. Several holes or slits in the penetrameter pass more radiation on to the film, and the appearance of the penetrameter image indicates sensitivity.

Two other nondestructive test methods for pipe are the eddy-current method and the ultrasonic method.

Eddy-current testing, which works on both ferrous and nonferrous metals, is widely used in pipe and tube manufacture. Radiography and ultrasonics are common testing methods for pipe joining. In high-speed inspection of newly made pipe, surrounding or external coils induce eddy currents in the pipe wall. Defects in the pipe cause an externally-sensed variation in the coil's impedance. Probe coils are used to search small areas in finished piping. Besides cracks and seams, eddy-current testing can find metal-structure differences;chemical composition and hardness are two of these differences.

Ultrasonic methods are growing in importance but are still not nearly as common as radiography. The upper right figure shows one of several ultrasonic methods applied to pipe-flaw detection. This particular method beams rapidly repeated short bursts of sound into the pipe wall at an angle of about 70 deg; these sounds are pitched far too high for the human ear to catch. The sound burst travels on a beam path, bouncing off the inner and outer walls. A defect will reflect part of the sound back to the transducer, which listens for reflections after each burst. The cathode-ray tube shows the image of sound intensity for each burst and reflection. Several hundred burst and listening periods can occur in a second, but the image of each is retained long enough to make it seem continuous. Calibration plates with small holes are an aid in ultrasonic inspection work.

Vital in nuclear work is test of welds for very small leaks. No material is absolutely leaktight; certain gases can permeate even through crystals. Detection methods such as bubbles formed in soapy water from escaping air have a sensitivity of no better than 0.3 cu cm per hour with an internal air pressure of 14.7 psig. More sensitive methods — the detection of radioisotopes re-emerging from leak paths that they have been allowed to penetrate — will detect as little as 3 millionths cu cm per year with an internal air pressure of 14.7 psig.

**To delve deeper into piping, start with these sources**

**U.S.A. B31 code; section B31.1** (power) and **B31.7** (nuclear). **B31.6** (chemical process) will soon appear.
Fifth edition of **"Piping Handbook,"** McGraw-Hill, 1967.
Latest editions of all five sections of **"Welding Handbook,"** American Welding Society.
Latest editions of such ASTM standards as:
**E8**—Tension testing of metallic materials
**E23**—Notched bar impact testing of metallic materials
**D1598**—Time-to-failure of plastic pipe under long-term hydrostatic pressure (for thermoplastics and thermosets)
Latest editions of **ASTM Standard Specifications,** including:
**A53**—Welded and seamless steel pipe
**A72**—Welded wrought-iron pipe
**A106**—Seamless carbon-steel pipe for high-temperature service
**A120**—Welded and seamless steel pipe for ordinary uses
**A335**—Seamless ferritic alloy steel pipe for high-temperature service
Plastics Pipe Institute's Technical Report on "Recommended method for obtaining hydrostatic-design basis for thermoplastic pipe."

a **Power** handbook

# Pumps

One of man's oldest aids, the pump today ranks second only to the electric motor as the most widely used industrial machine. Anything that will flow is pumped— from highly volatile ether to thick muds and sludges. Molten metals and liquids at 1000 F, or higher, pose few real problems for modern pumps.

Though the origin of pumps is lost in antiquity, we do know that crude pumping devices provided water for ancient Egypt, China, India, Greece and Rome. Today the U.S. alone draws more than 200 billion gallons each day from its water resources and pumps move almost every drop. Of this total, an impressive 80 billion gallons is said to be industry's share.

To meet these demands we find an almost confusingly large variety of available pumps. They range from tiny adjustable displacement units to giants handling well over 100,000 gallons per minute. Number of designs soars into the hundreds, some differing in elements as small as packing glands, some in the entire principle of operation.

It's neither possible nor desirable to cover every variation in a concise practical handbook such as this. So we've made a highly selective choice of widely used industrial pumps of all classes and types — the pumps you're likely to run into in your work. And we've stuck to units using mechanical means to move a liquid from one point to another, putting aside for a time such devices as ejectors, hydraulic rams, etc.

So you'll find the important facts about industrial pumping in easy-to-read form in the following 31 pages. Put them to work improving the effectiveness of your pumping operations.

# These quick guides to the world of pumps show the major

| CLASS | TYPE | | IMPORTANT GENERAL FACTS |
|---|---|---|---|
| CENTRIFUGAL | Volute | | The majority of centrifugal pumps built in the U.S. today are volute type. They are available as horizontal or vertical pumps, single- or multistage for wide flow ranges |
| | Diffuser | | Diffuser-type centrifugals find many uses as multistage high-pressure units. Originally more efficient than volute-type pumps, today efficiency of both types is about equal |
| | Mixed-flow | | Mixed-flow centrifugal pumps are ideal for low-head large-capacity applications. Usually vertical, they have a single-inlet impeller. Some horizontal units are built |
| | Axial-flow | | Axial-flow units, often called propeller pumps, develop most of their head by lifting action of vanes, are usually vertical, and best suited for low heads, large capacities |
| | Turbine or regenerative | | For clear liquids, turbine pumps, either horizontal or vertical, fill a need between other centrifugal and usual rotary designs. They are low- to medium-capacity, high-head |
| ROTARY | Gear<br>Vane | | Gear pumps consist of two or more gears (spur, single- or double-helical teeth), while vane pumps have a series of vanes, blades or buckets turned by a single rotor. This rotary class also includes lobe or shuttle-block designs |
| | Cam-and-piston<br>Screw | | Cam-and-piston rotaries, like most types in this class, are positive-displacement units, giving steady discharge flow. Along with screw-type pumps, and related designs, they handle a wide range of nonabrasive viscous liquids |
| RECIPROCATING | Direct-acting | | Old standbys for years, direct-acting steam pumps now are available in many designs for handling cold or hot water, oil, and a wide range of industrial liquids of many types |
| | Power | | Power pumps are driven from outside through a crankshaft or other device. Capacities range from very low to medium flows, at pressures up to 15,000 psi, or higher |
| | Crank-flywheel | | Crank-and-flywheel pumps are one form of reciprocating power pump, so designated to distinguish them from power pumps using, for example, an eccentric as drive mechanism |

| | Centrifugal | | Rotary | Reciprocating | | |
|---|---|---|---|---|---|---|
| | Volute and diffuser | Axial flow | Screw and gear | Direct-acting steam | Double-acting power | Triplex |
| Discharge flow | Steady | Steady | Steady | Pulsating | Pulsating | Pulsating |
| Usual max. suction lift, ft | 15 | 15 | 22 | 22 | 22 | 22 |
| Liquids handled | Clean, clear; dirty, abrasive; liquids with high solids content | | Viscous, nonabrasive | Clean and clear | | |
| Discharge pressure range | Low to high | | Medium | Low to highest produced | | |
| Usual capacity range | Small to largest available | | Small to medium | Relatively small | | |
| How increased head affects: | | | | | | |
| Capacity | Decrease | | None | Decrease | None | None |
| Power input | Depends on specific speed | | Increase | Increase | Increase | Increase |
| How decreased head affects: | | | | | | |
| Capacity | Increase | | None | Small increase | None | None |
| Power input | Depends on specific speed | | Decrease | Decrease | Decrease | Decrease |

## DEFINITIONS

PUMPING is the addition of energy to a liquid to *move it from one point to another*

CENTRIFUGAL PUMPS employ centrifugal force to develop a pressure rise for moving a liquid

ROTARY PUMPS use gears, vanes, pistons, screws, cams, segments, etc, in a fixed casing to produce steady positive displacement of a liquid

RECIPROCATING PUMPS use pistons, plungers, diaphragms or other devices to positively displace a given volume of liquid during each stroke of the unit

IMPELLER is the rotating element in a centrifugal pump through which liquid passes and by means of which energy is imparted to the liquid

CASING of a centrifugal pump is the housing surrounding the impeller. It contains the bearings for supporting the shaft on which impeller mounts

LIQUID PISTON OR PLUNGER *of a reciprocating* pump is the moving member that contacts the liquid and imparts energy to it

SINGLE-STAGE centrifugal pump is one in which total head is developed by one impeller

MULTISTAGE centrifugal pump is one having two or more impellers acting in series in one casing

3

# Pumps . . . major classes and types

The world of pumps can be extremely confusing to newcomers—and even to some oldtimers. Diagram, *left*, is designed to clear up much of the mystery and confusion surrounding pump *classes* and *types*. You might call it your road map to the world of pumps. Based on often-used standard classifications, it incorporates a number of useful facts that are a big help in pump selection and application.

**Three classes of pumps** find use today—*centrifugal, rotary* and *reciprocating*. Note that these terms apply only to the mechanics of moving the fluid, not to the service for which the pump is designed. This is important, because many pumps are built and sold for a specific service, and in the complex problem of finding which has the best design details we may overlook the basic problems of class and type.

**Each classification** is further subdivided into a number of different types, diagram *left*. For example, under the rotary classification we have cam, screw, gear and vane pumps. Each is a particular type of rotary pump.

To go one step further, let's take a brief look at a fuel-oil pump in wide use today. It is a rotary three-screw type available with rotors of a number of different materials and four means of balancing axial thrust.

The last two items are important *details* in pump application; first two are keys to classification of the unit. The Hydraulic Institute recommends that the standard classification be considered as applying to type only, leaving the builder to use the details he has developed or standardized for that type of pump. So in selecting a pump we often find we must compare, detail for detail, a number of makes. Broad breakdown in diagram comes in handy then.

**Our next consideration** is a wide statement of the general characteristics of a given class of pumps. Table, *above left*, does just this for us.

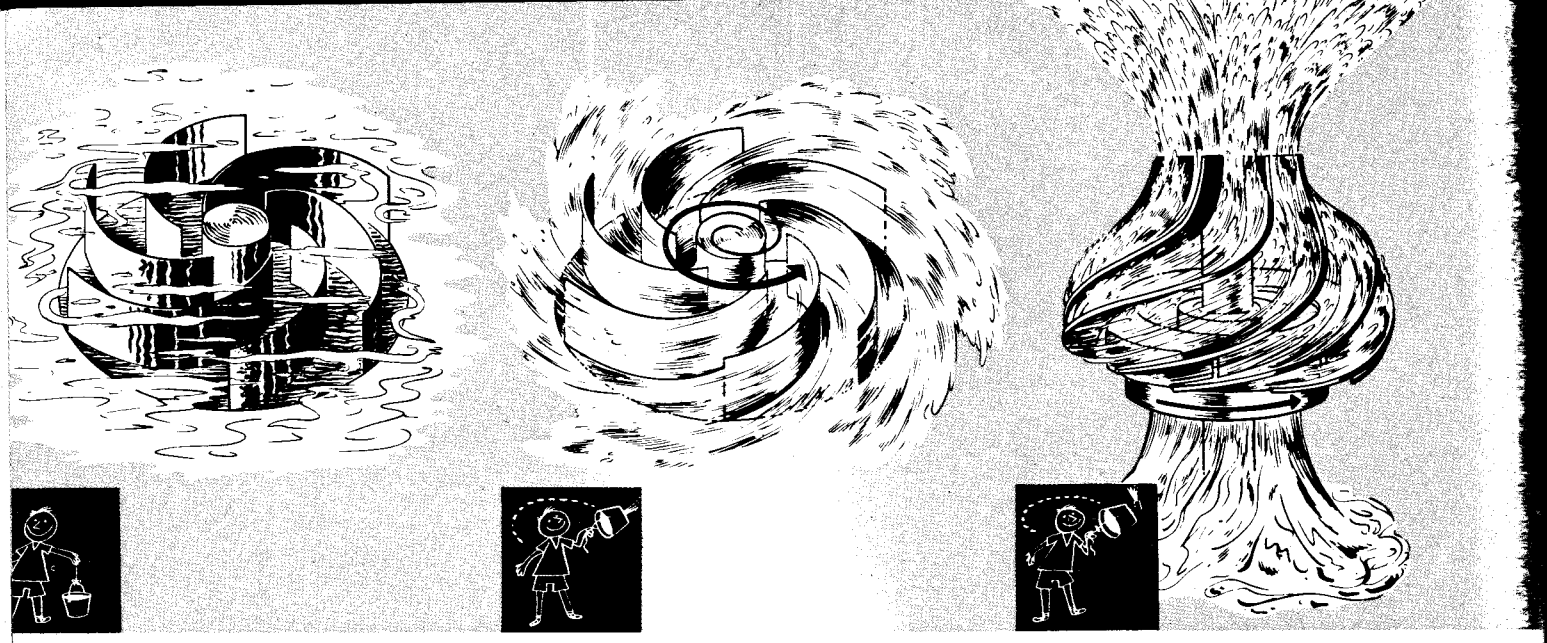
For example, if we want to handle relatively small capacities of clean, clear liquids at high head, we can refer to the table. In any problem of this type we must remember that suction lift should not exceed recommended limit. Capacity in gallons per minute (gpm) determines pump size and influences classification. Nature of fluid is also involved, as is pump construction. Head is a big factor.

**Table shows** a reciprocating pump is suitable for the general conditions we have in mind—small capacity, high head, clean, clear liquids. Then, depending on job needs, we may choose a piston or plunger type, direct-acting, crank-and-flywheel, or power type. It may be simplex, duplex, triplex, or have a larger number of cylinders.

Once we've settled these items we're ready to study valve details, materials, drives, etc. In general, you'll find that pump details are greatly influenced by job requirements. Thus the particular arrangement of a centrifugal pump may depend as much on piping, space and working conditions as on any other existing factors. Drive chosen for the pump may be fixed by the pump speed, plant heat balance, power supply available or cost of a particular fuel in the area. But again, these are details, to be decided after we find a pump suitable for the hydraulic conditions we must meet. And the key to meeting the hydraulic conditions is the right class and type of pump.

Where two or more different units meet hydraulic needs, we must go one step further and decide which pump is best for the installation. We may want or need low first cost, long life or maximum operating economy. Normally we do not find all in one package. So we must decide which is most important and go ahead from there.

**Getting the right pump** is much like coming to a fork in the road. Our map tells us which way to turn. Once on the right road all we need do is watch our route markers. The next 29 pages do just that for you in the world of pumps.



## CENTRIFUGAL

As a boy you probably whirled around your head a bucket on the end of a rope, just like the little guy in the three sketches above. As you recall, the water stayed in the bucket just as long as you kept it turning at a fair speed. The force that kept the water in the bucket is at work in centrifugal pumps.

Imagine an impeller at rest in water, *above left*. This is like the lad's bucket before he starts whirling it. Now rotate the impeller, *middle sketch*. Water will fly out from between the blades just as it would squirt out of the whirling bucket if it had a hole in the bottom.

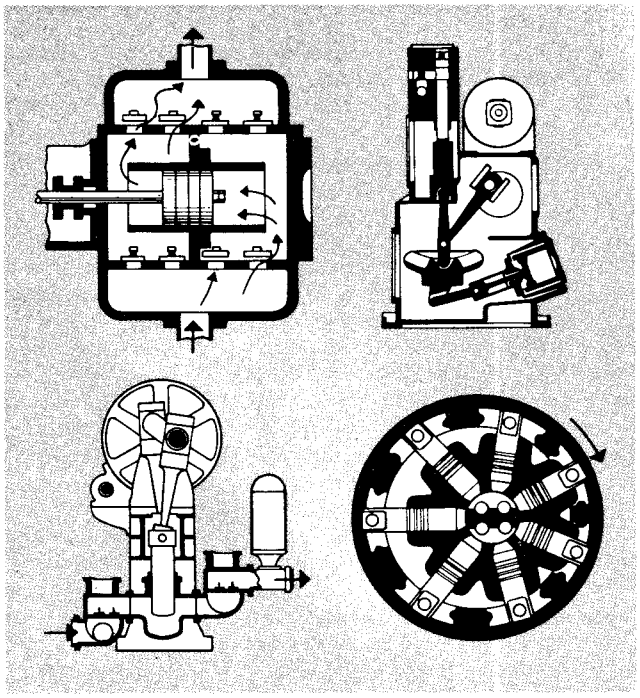
The force causing the water to leave the impeller (or the bucket) is *centrifugal force* and that's where pumps of this class get their name. They depend on centrifugal action even though details differ, as we'll see later.

Going back to the middle sketch, as the impeller throws out liquid, more rushes into the center where the lowest pressure exists, and where a suction pipe is normally fitted. This liquid too is thrown out, is followed by more, and we have the steady discharge characteristic of centrifugals.

Once the liquid is being thrown from the impeller we must guide it to its destination. Otherwise we've accomplished little more than make a big splash.

By putting the impeller in a casing we can change flow from haphazardly outward to controlled movement in the direction we want. With vanes like those of the deepwell pump in the righthand sketch we can even turn the flow upward. A casing, with or without vanes, acts something like a hose attached to the bottom of the boy's bucket.

The result is a workable pump for imparting energy to a liquid at one point to cause it to move to another.



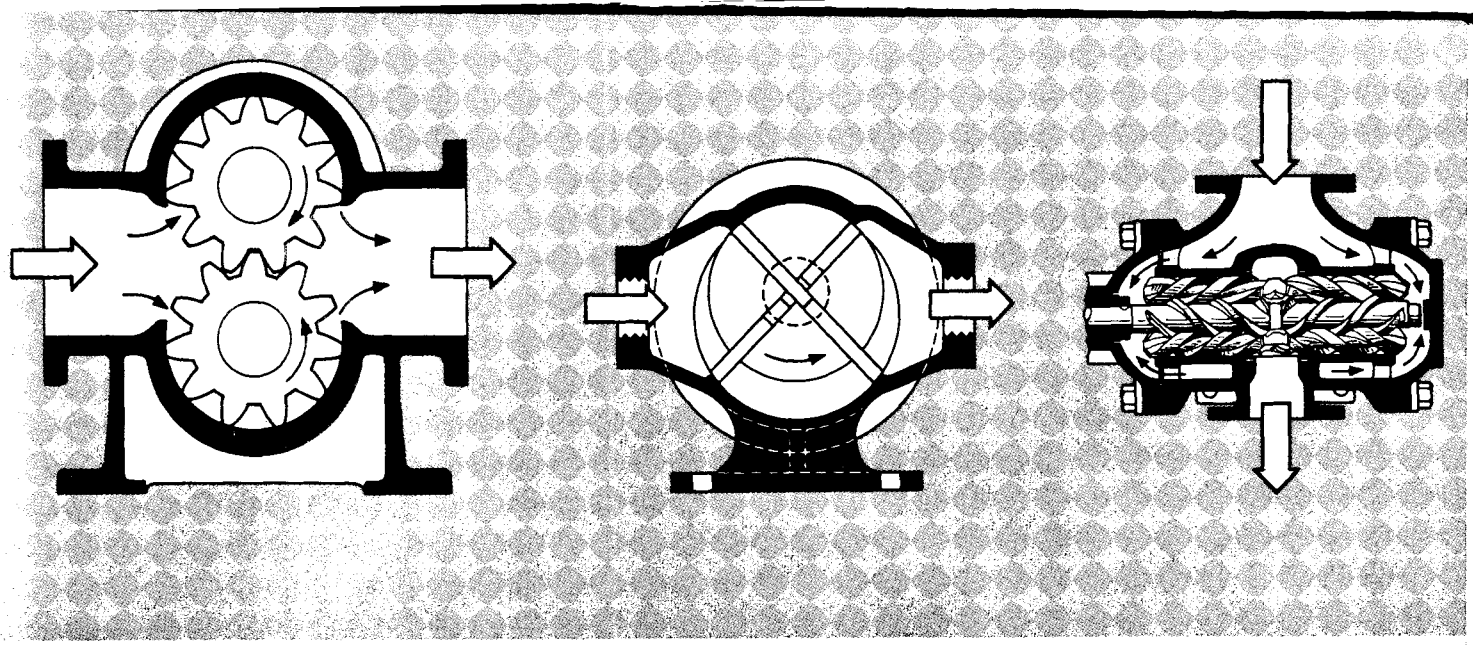
## RECIPROCATING

Long of major importance in the pumping field, reciprocating units today are finding many new uses, particularly in the fields of metering and proportioning, and where extremely high pressures are needed.

Direct-acting steam pumps, *top left,* have two sets of valves in the liquid end. When the piston moves to the left as shown, liquid is drawn in through the righthand set of suction valves and liquid previously drawn into the cylinder is discharged through the upper left set of discharge valves. This is a double-acting pump, liquid being discharged on every stroke. The actual arrangement of the valves differs in various designs.

Power pumps, *top right and lower left,* have a number of different arrangements for suction and discharge valves. In these two single-acting units, liquid is drawn into the cylinder during one stroke of the plunger. On the next stroke, the plunger forces liquid through the discharge valves into the pump outlet.

Radial-piston pumps, *lower right,* one of many relatively recent designs, have their pistons attached to an outer ring whose center of rotation can be changed. Moving the ring to an eccentric position produces suction and discharge through valves in the center of the pump. Reversing the direction of ring rotation reverses liquid flow. A large number of other designs are discussed later, pp 90-95.



**ROTARY** Like reciprocating pumps but unlike centrifugals, most rotary pumps are positive-displacement units — that is a given quantity of liquid is discharged for each revolution of the shaft. Like the centrifugal pump, flow is usually steady, without large pressure pulsations.

Rotary gear pumps, *above left,* have two or more gears in a casing and during rotation the liquid fills the spaces between the gear teeth on the suction side. From there it is carried around and squeezed out as the teeth mesh on the other side of the pump.

Sliding-vane rotary pumps, *above center,* are built in a number of different designs. In the type shown, the vanes move in and out of the rotor, which is set off-center in the casing. When the rotor turns counterclockwise, liquid flows into the cavity formed by rotor bottom and casing wall.

As the rotor turns, it brings the next vane into position to trap the liquid in the cavity. Further rotation forces the liquid around and out the discharge opening of the pump. The vanes are held against the inner wall of the casing by centrifugal force produced by rapid rotation of the rotor.

Screw pumps, *above right,* draw the liquid into one or both ends of the rotor or rotors, where it is trapped in the pockets formed by the threads. It is moved along to the discharge point much like a nut on a thread. Screw-type rotary pumps may have one, two or three screws. When only a single screw is used, liquid enters at one end, is discharged at the other. The screw runs in a double-threaded helix. Clearance is an important factor in many rotary-pump designs that are used today.

Later, pp 88, we'll discuss the large number of other rotary-pump designs used for a variety of industrial services.

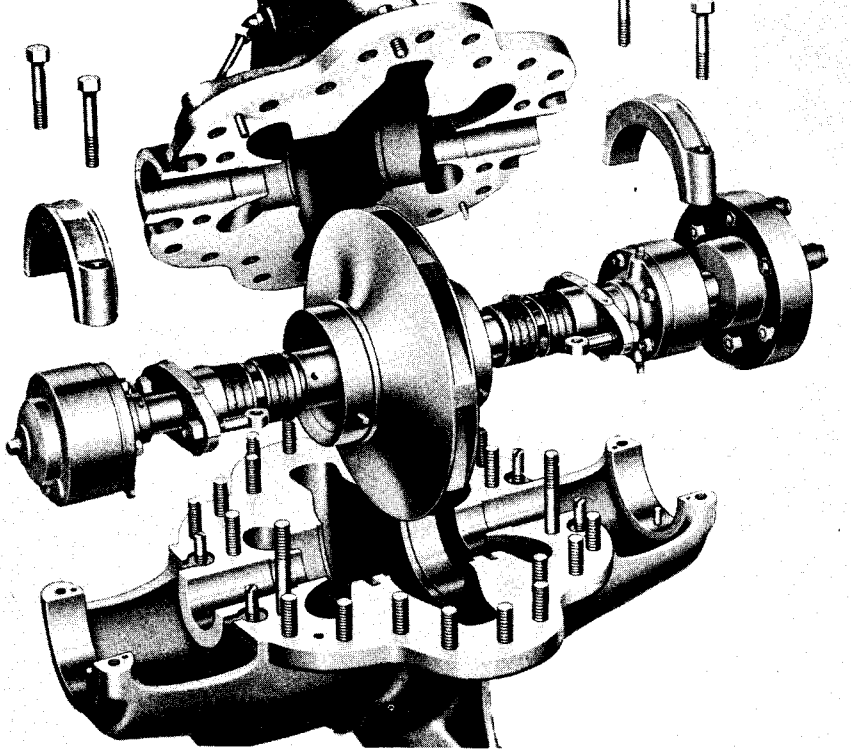
# How pumps work

## OTHER PUMPING PRINCIPLES

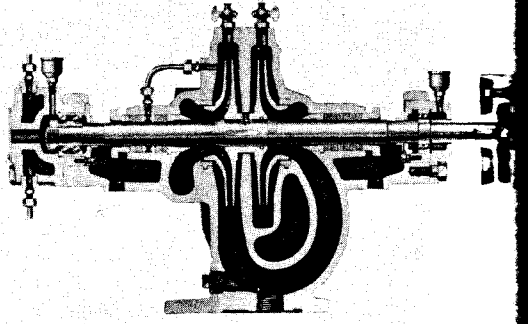
Some of the most interesting recent design developments are in pumps for process and nuclear-energy applications. To handle liquid metals, for example, we now have electromagnetic pumps, in which electrical energy is applied directly.

Electromagnetic pumps include the Faraday type for ac or dc power, the ac linear-induction design (a modification of this is called the Einstein-Szilard pump) and the electromagnetic centrifugal. These, and other similar designs, represent new approaches to the problem of moving a liquid from one point to another.

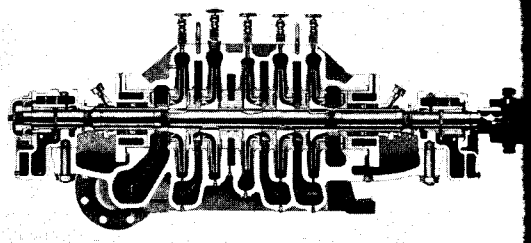
Among older ideas for moving liquids there are, of course, the familiar air lift, hydraulic rams, and the Humphrey pump. Here, however, we stick to common mechanical methods.



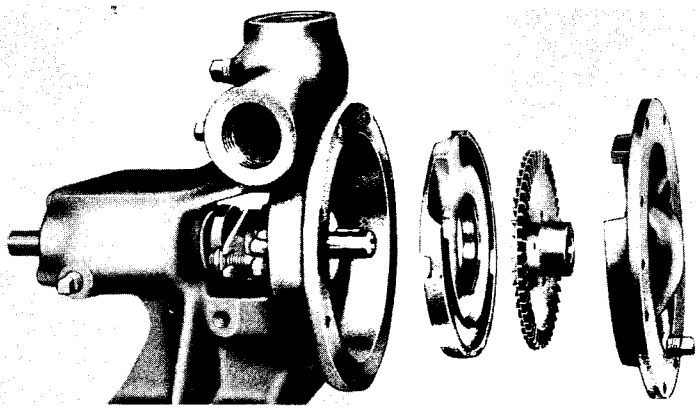
**SINGLE-STAGE** general-purpose pump has horizontally split casing, water-sealed stuffing boxes, cast-iron double-suction casing. The impeller is made of bronze



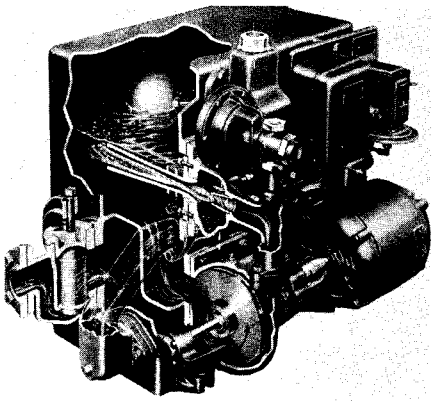
**TWO-STAGE** horizontally split pump has opposed impellers, ball-type bearings



**MULTISTAGE** single-suction opposed-impeller pump for continuous heavy duty



**HORIZONTAL TURBINE PUMP,** single stage, is self-venting to prevent vapor binding. Units like this are built with standard stuffing boxes, or with a mechanical seal



**ENCLOSED-TYPE** non-overload impeller on stainless-steel shaft for vacuum service

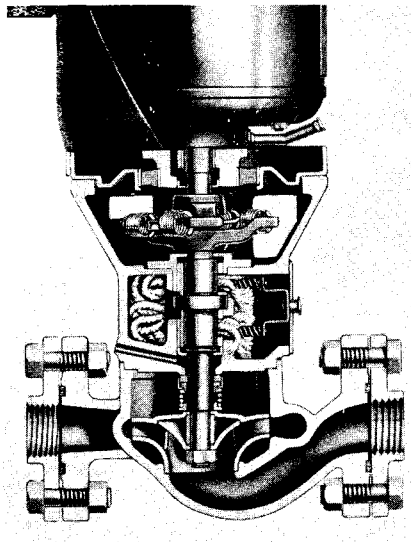
# Centrifugal pumps

Earlier we saw how modern pumps are classified and typed. Now we're ready to take a closer look at centrifugal pumps — the most widely used units.

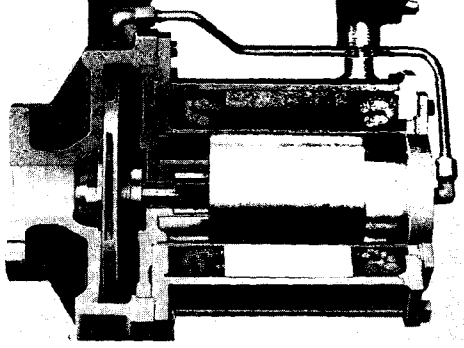
Illustrations on these two pages are a small sampling of today's designs. Study shows that though all come under one broad classification, intended application is a major factor in impeller and casing design, materials used, and other mechanical and hydraulic features. For these reasons we find pump builders stressing ultimate use somewhat more than classification and type.

Thus centrifugal pumps are termed boiler-feed, general-purpose, sump, deep-well, refinery (hot oil), condensate, vacuum (heating), process, sewage, trash, circulating, self-priming, sanitary, bait, booster, paper stock, chemical, fire, jet, sand, slurry, ash, glass, stoneware, submersible, tail-water, etc. In general, each has specific features of design and materials recommended by the builder for the particular service. This makes selection and application easier.

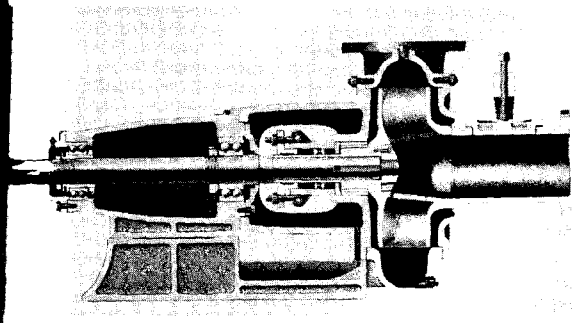
Another subdivision grows out of broad structural features. Thus we find horizontal and vertical units, close-coupled designs, single- and double-suction impellers, horizontally split casings and barrel casings, etc. Correct evaluation of all these variations is one of the big jobs in selecting a pump.



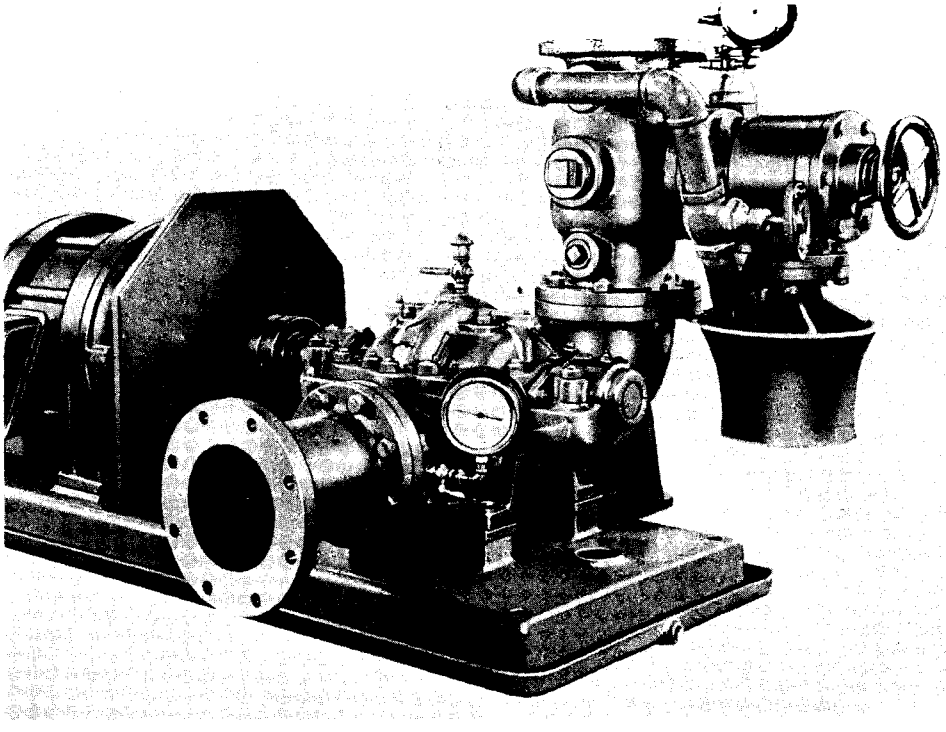
**SINGLE-STAGE** pump with sleeve bearings and mechanical seal for hot-water uses



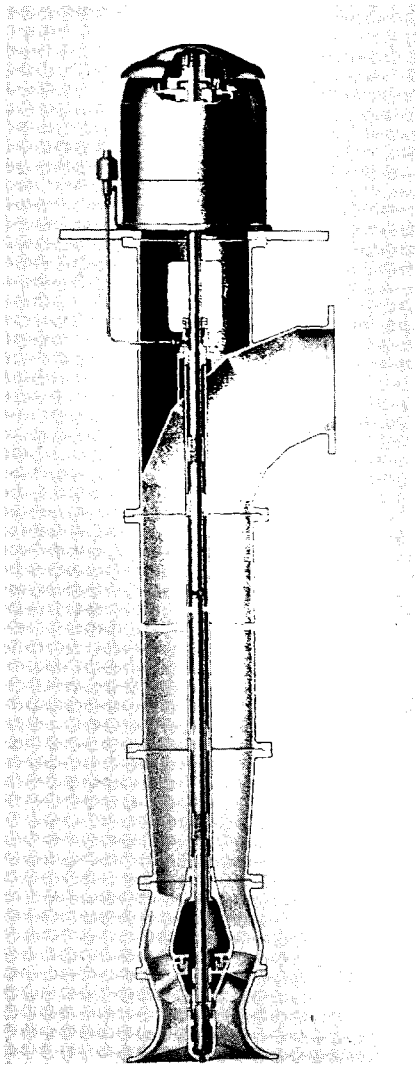
SEAL-LESS leakproof combined motor-pump has no stuffing boxes, uses no lubricant



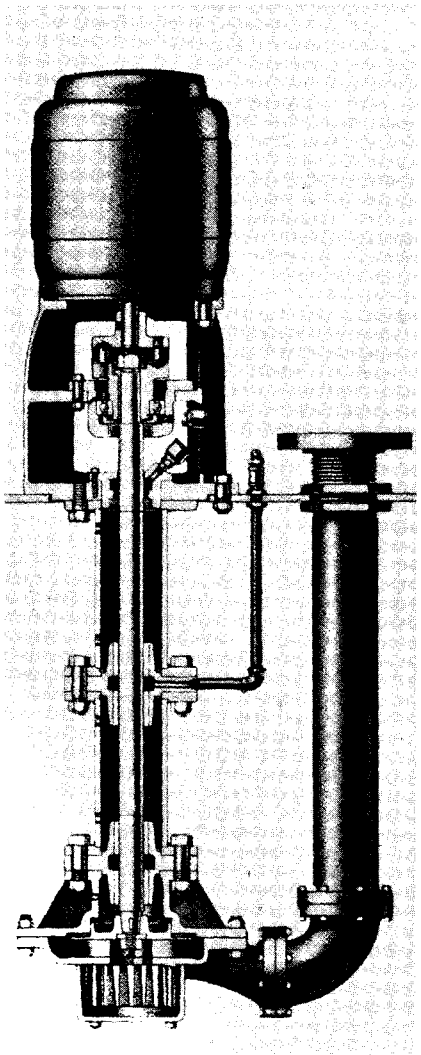
NON-CLOGGING PUMP: 2-bladed impeller, ball bearings, removable suction cover



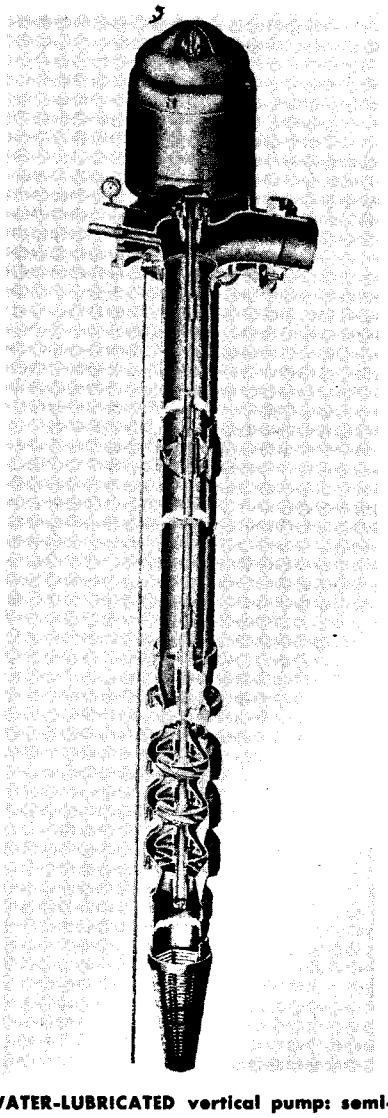
SUCTION SIDE of a single-stage fire pump, complete with motor and fittings. Pumps and fittings for this service are laboratory tested before underwriters' approval



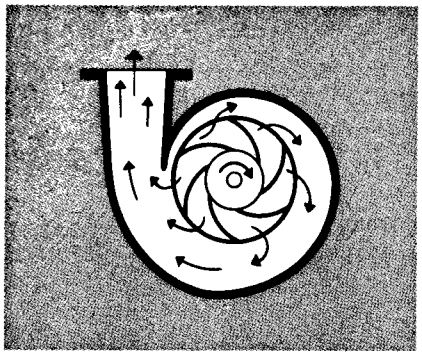
MIXED-FLOW vertical pump may be either water or oil lubricated, depending on job



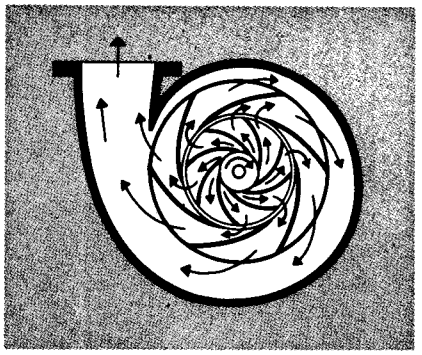
VERTICAL single-stage unit has semi-open impeller, ball and sleeve shaft bearings



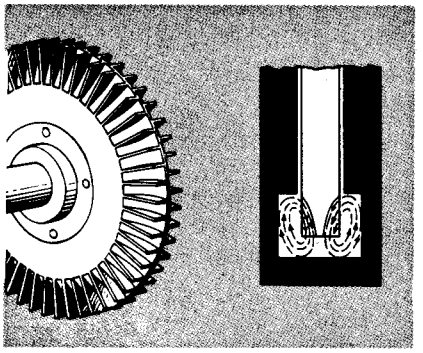
WATER-LUBRICATED vertical pump: semi-open impellers, open line-shaft bearings



**VOLUTE converts velocity energy of the liquid into static pressure (read in psi)**



**DIFFUSER changes flow direction, aids in converting velocity energy to pressure**



**TURBINE pump adds energy to the liquid in a number of impulses during rotation**

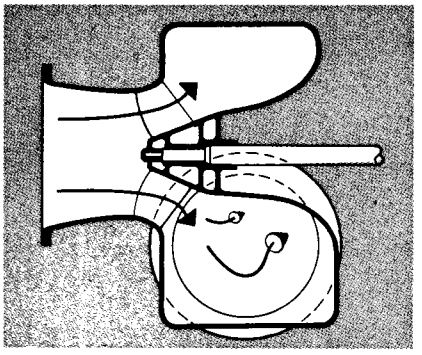
## Pump action

In volute-type pumps the impeller discharges into a progressively expanding spiral casing, proportioned to gradually reduce liquid velocity. Thus velocity energy is changed to pressure head in the volute.

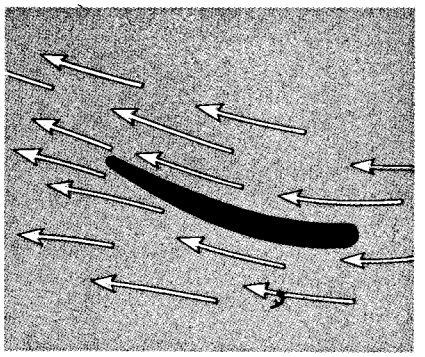
Stationary guide vanes surround the runner in a diffuser-type pump. These gradually expanding passages change the direction of liquid flow and convert velocity energy to pressure head.

Liquid in a turbine pump is picked up by the impeller's vanes and whirled at a high velocity for nearly one revolution in an annular channel in which the impeller turns. Energy is added to the liquid in a number of impulses, so it enters the discharge at high velocity.

Mixed-flow pumps develop their head partly by centrifugal force and partly by the lift of the vanes on the liquid. Propeller pumps develop most of their head by the propelling or lifting action of the vanes on the liquid.



**MIXED-FLOW units use both centrifugal force and lift of vanes on the liquid**



**PROPELLER pump develops most of its head by propelling action of vanes on liquid**

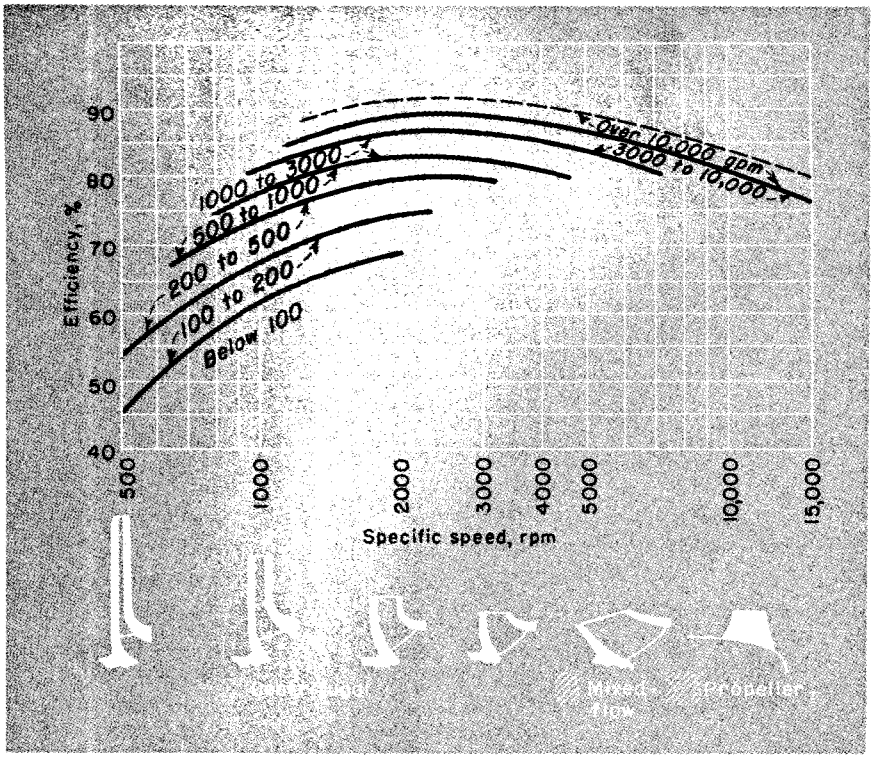
## Specific speed

Specific speed is an index of pump type, using the capacity and head obtained at the point of maximum efficiency. It determines the general profile or shape of the impeller. In numbers, specific speed is the rpm at which an impeller would run if reduced in size to deliver 1 gpm against a total head of 1 ft.

Impellers for high heads usually have low specific speed; impellers for low heads have high specific speed.

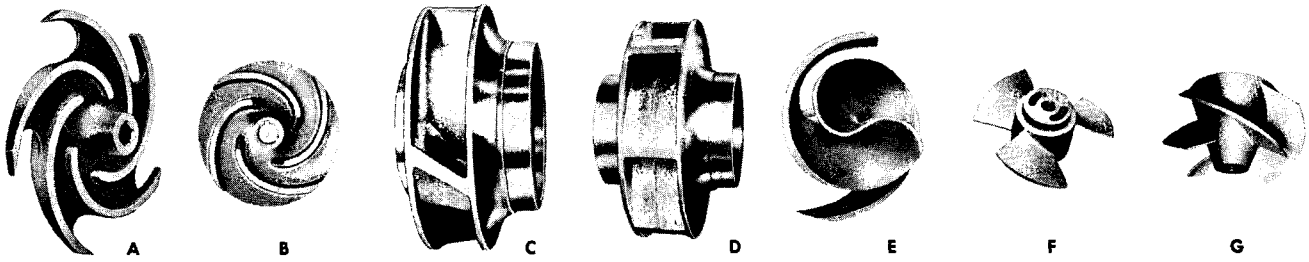
As diagram, *right*, shows, each impeller design has a specific-speed range for which it is best adapted. These ranges are approximate, without clear-cut divisions between them. Chart gives general relations between impeller shape, efficiency and capacity.

Suction limitations of different pumps bear a relation to the specific speed. The Hydraulic Institute publishes charts giving recommended specific speed limits for various conditions.




**SPECIFIC SPEED is approximately related to impeller shape and efficiency, as shown by these curves. There is no sharp dividing line between various impeller designs**

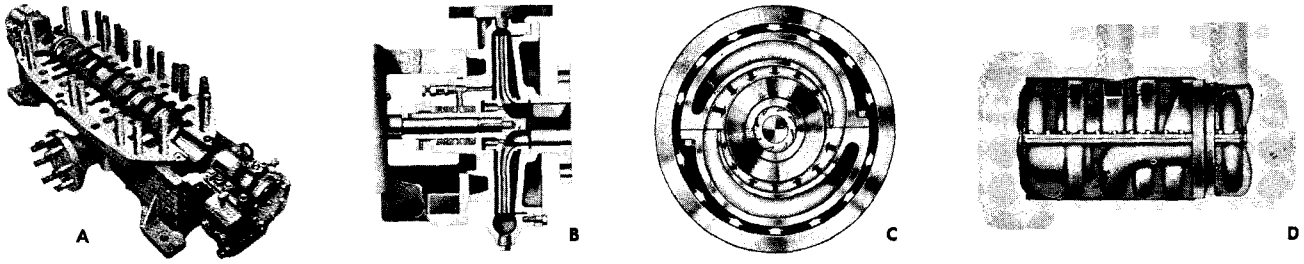
## Impellers




Besides being classified according to specific speed, an impeller is also typed as to how the liquid enters, its vane details, and use for which it is intended.

*Open* impellers, *A*, have vanes attached to a central hub with relatively small shrouds. *Semi-open, B,* have a shroud, or wall, on only one side. *Closed* impellers, *C* and *D,* have shrouds on both sides to enclose liquid passages. *Single* or *end-suction* units, *C,* have liquid inlet on one side; in *double-suction* type, *D,* liquid enters both sides. *E, F* and *G are paper-stock, propeller and mixed-flow* designs.

## Casings

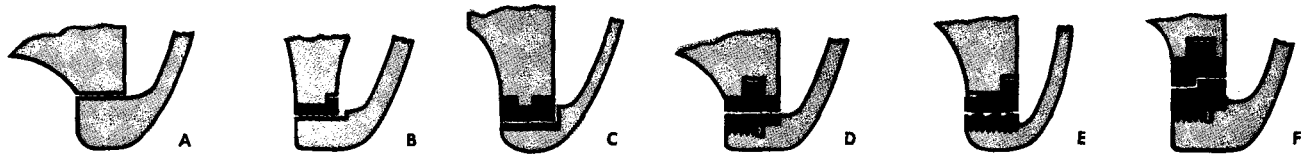



Centrifugal-pump casings may be split *horizontally, A, vertically, B,* or *diagonally* (at an angle other than 90 deg).

Horizontally split casings are also termed *axially* split. Both suction and discharge nozzles are normally in lower half of casing; upper half lifts for easy inspection. Vertically split casings are also called *radially* split. They're used in close-coupled or frame-mounted end-suction designs.

*Barrel casings, C* and *D,* are used on high-pressure diffuser and volute pumps. Inner casing fits in outer barrel. Discharge pressure acting on inner case provides seal.

## Wearing rings

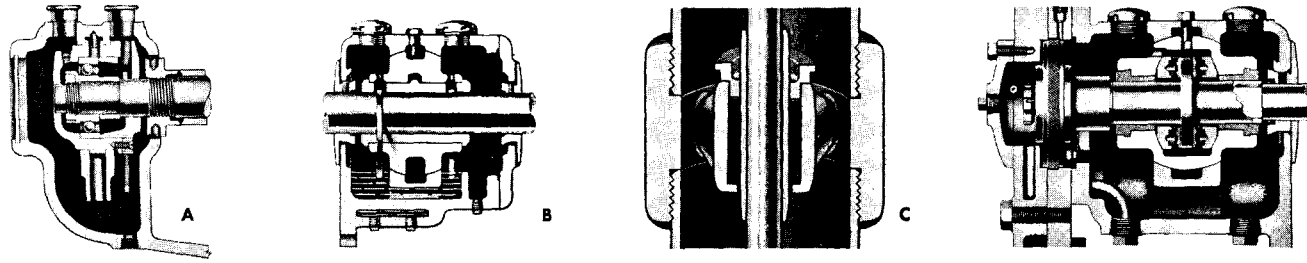



To prevent costly wear of casing and impeller at the running joint, wearing rings, also called casing rings, are installed. Where these rings are removable, as they usually are, they can be replaced at a fraction of the cost of a new impeller or pump casing that might otherwise be needed.

Seal *A* is a plain flat joint. Similar joint, *B,* has a flat ring mounted on the pump casing. At *C* the ring fits into a casing groove; impeller has a similar ring.

In designs *D, E,* and *F,* rings are fitted to both casing and impeller. Form varies with pressure, service, etc.

## Bearings



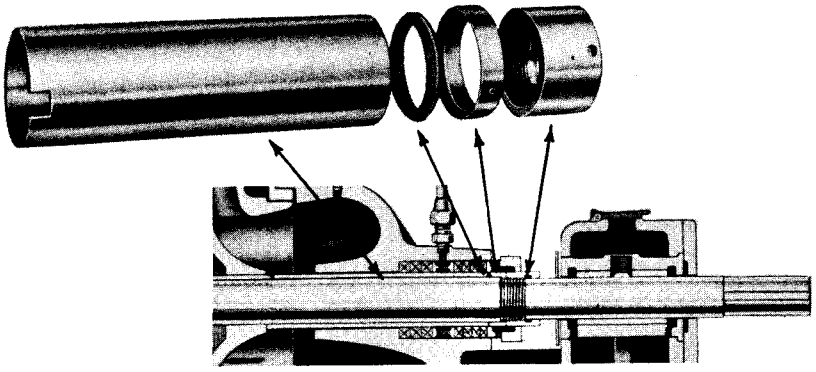

Practically every type of bearing has been used in centrifugal pumps. Today, *ball, sleeve* and *Kingsbury* bearings find most common use. Many pumps are available with more than one type of bearing to meet different needs.

Ball bearings, *A,* may be of single- or double-row type. Spherical roller bearings are widely used for large shafts.

Sleeve bearings, *B* and *C,* may be either horizontal or vertical. In the latter, water is often the lubricant.

Kingsbury thrust bearings, *D,* find use in larger pumps. Design resembles that used in other rotating machinery.

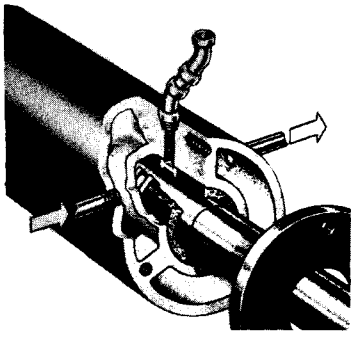
## Shaft and interstage sleeves

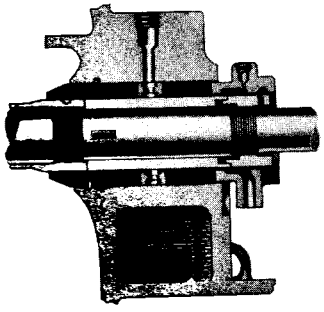


Sleeves protect shaft against corrosion, erosion and wear affecting its strength. Many forms are used on large pumps but on small ones sleeve is often left off to cut hydraulic and stuffingbox losses. Shaft is then made of a metal that is sufficiently corrosion- and wear-resistant for satisfactory life.

Interstage sleeves guard multistage pump shafts. In some, long hub on impeller replaces interstage sleeve.

## Lantern rings



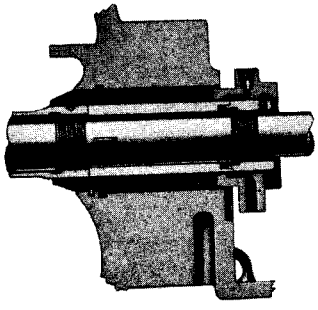


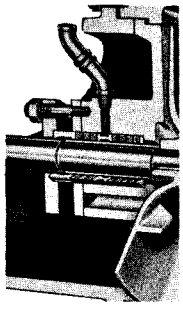
These are used to prevent air leakage into pump when running with a suction lift and to distribute sealing liquid uniformly around annular space between box core, shaft-sleeve surface.

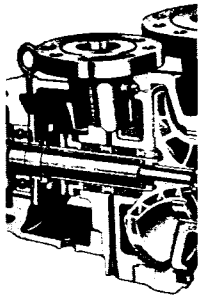
Also called seal cages and waterseal rings, they receive liquid under pressure from pump or independent source.

Grease sometimes serves as sealing medium when clear liquid isn't available or can't be used (sewage pumps).

## Stuffing boxes



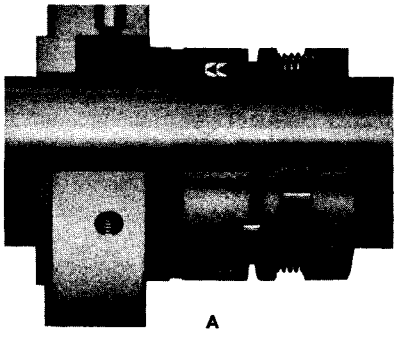




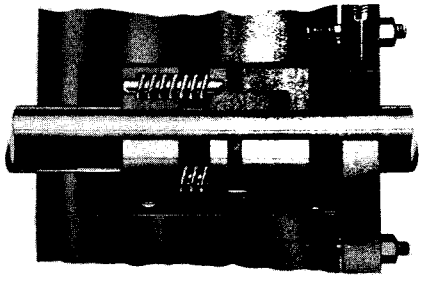
Stuffing box stops air leaking into casing when pressure is below atmospheric; holds leakage out of casing to a minimum when pressure is above.

Sketches show solid-packed box, which has no lantern rings; two injection designs, which do. On pumps handling hot liquids, or having high stuffing-box pressures, box is often water-jacket cooled. In some, coolant and pumped liquid mix.

## Mechanical seals



A



B

Mechanical seals in wide variety serve where leakage is objectionable. They also find use where stuffing-boxes can't give adequate leak protection.

Sealing surfaces are perpendicular to pump shaft and usually comprise two polished lubricated parts running on each other. Though not guaranteed leakproof, leakage is usually nil.

*Outside* type, *A*, is used where gritty liquids or leakage retained in stuffing box would be undesirable. *Inside*, *B*, finds much use for volatile liquids.

## HYDRAULIC INSTITUTE MATERIALS SELECTIONS AND DESIGNATIONS

| Institute selection no. | Corresponding national society standards designation ASTM | ACI | AISI | Remarks |
|---|---|---|---|---|
| 1 | A 48, Grades 20, 25, 30, 35, 40, & 50 | ..... | ..... | Gray iron — six grades |
| 2 | B 143, 1 B & 2A; B 144, 3A; B 145, 4A | ..... | ..... | Tin bronze — six grades (includes two grades covered in detail in *Standards of Hydraulic Institute*) |
| 3 | A 216, WCB | ..... | 1030 | Carbon steel |
| 4 | A 217, C5 | ..... | 501 | 5% Chromium steel |
| 5 | A 296, CA15 | CA15 | 410 | 13% Chromium steel |
| 6 | A 296, CB30 | CB30 | ... | 20% Chromium steel |
| 7 | A 296, CC50 | CC50 | 446 | 28% Chromium steel |
| 8 | A 296, CF8 | CF8 | 304 | 18-8 Austenitic steel |
| 9 | A 296, CF8M | CF8M | 316 | 18-8 Molybdenum austenitic steel |
| 10 | ..... | Cn-7MCu | ... | A series of highly-alloyed steels normally used where the corrosive conditions are severe |
| 11 | ..... | ..... | ... | A series of nickel-base alloys |
| 12 | ..... | ..... | ... | High-silicon cast iron |
| 13 | ..... | ..... | ... | Austenitic cast iron |
| 14 | ..... | ..... | ... | Monel metal |
| 15 | ..... | ..... | ... | Nickel |

NOTE: ASTM — American Society for Testing Materials ACI — Alloy Casting Institute AISI — American Iron and Steel Institute

# Materials for centrifugal pumps

### MATERIALS FOR PUMPING VARIOUS LIQUIDS

| Liquid | Condition | Material selection |
|---|---|---|
| Acid, acetic | Conc cold | 8, 9, 10, 11, 12 |
| Acid, hydrochloric | Commt conc | 11, 12 |
| Acid, nitric | Conc boiling | 6, 7, 10, 12 |
| Acid, sulfuric | >77%, cold | C, 10, 11, 12 |
| Alcohols | | A, B |
| Asphalt | Hot | C, 5 |
| Beer | | A, B |
| Beet juice | | A, B |
| Brine, CaCl | pH>8 | C |
| Brine, CaCl | pH<8 | A, 10, 11, 13, 14 |
| Brine, NaCl | <3%, cold | A, 6, 13 |
| Brine, NaCl | >3%, cold | A, 8, 9, 10, 11, 13, 14 |
| Calcium hypochlorite | | C, 10, 11, 12 |
| Carbon tet | Anhydrous | B, C |
| Formaldehyde | | A, 8, 9, 10, 11 |
| Gasoline | | B, C |
| Glue | Hot | B, C |
| Lead | Molten | C, 3 |
| Milk | | 8 |
| Molasses | | A, B |
| Mustard | | A, 8, 9, 10, 11, 12 |
| Oil, crude | Hot | 3 |
| Oil, fuel | | B, C |
| Oil, kerosene | | B, C |
| Oil, lube | | B, C |
| Sewage | | A, B, C |
| Soda ash | Hot | 8, 9, 10, 11 |
| Sodium hydroxide | Aqueous sol | C, 5, 8, 9, 10, 11, 13, 14 |
| Sugar | Aqueous sol | A, 8, 9, 10, 11, 13 |
| Tar | Hot | C, 3 |
| Water, feed | Not evaporated | |
| | pH>8.5 | C |
| | pH<8.5 | B |
| | Evaporated, any pH | 4, 5, 8, 14 |

Eight important factors affecting choice of materials for centrifugal pumps are: suspended-solids abrasiveness, corrosion resistance, electrochemical action, liquid temperature, head per stage, discharge pressure, structural considerations, pump load-factor.

**Tables,** *above and left,* summarize the broad experience of pump makers and users with various materials and liquids. Materials listed are applicable to all classes of pumps as far as corrosion-resistance characteristics are concerned. But in some pumps, design considerations impose differing physical requirements.

Obviously, a tabulation cannot recognize all possible construction variations but must concern itself primarily with the general problem of corrosion. This must be remembered when evaluating merits of the various materials.

**Materials** listed are those commonly used in the principal parts of the pump, such as casing, impeller, cylinders, etc. Trim items like sleeves, glands, rings, valves, etc, may differ to meet some mechanical requirement but the material selected should be suitable for the environment.

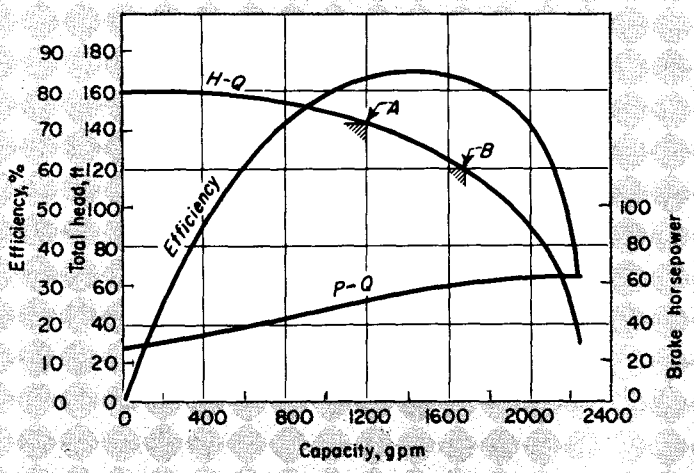
Because of the many variables, no one can say with certainty that some one material will best withstand corrosive attack of a given liquid. So more than one type is usually listed in the table, *left.* Order does not indicate relative superiority — factors predominant in one installation may be almost nonexistent in another.

**Symbols** used in table, *left,* are *A,* an all-bronze pump, *B* for bronze-fitted pumps, and *C* for all-iron pumps. Other materials, including a large number special corrosion-resistant types, are listed in table directly above.

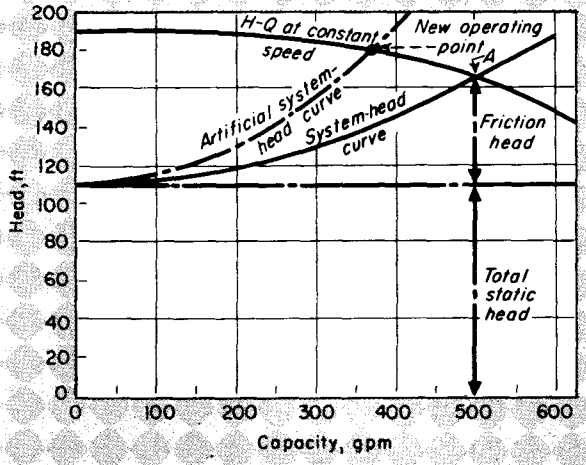
In *Standards of Hydraulic Institute,* par E-19, *Data Section,* a helpful form to aid the pump manufacturer select the best materials for a given liquid is presented. It is extremely useful to all prospective pump purchasers.

Bronze finds much use in centrifugal pumps because it doesn't rust, is easier to machine than iron, can be given a smoother finish and theoretically permits higher efficiencies. But its limitations may prevent its use.

**Casings** are cast iron in bronze-fitted and all-iron pumps. For corrosive, high-temperature and high-pressure jobs, others materials find use. Bronze casings are popular for mildly corrosive liquids, cast or forged steel for higher pressures and temperatures.




**CHARACTERISTIC CURVES for a given impeller size and design show head, hp, capacity, efficiency**




**SYSTEM-HEAD curve is valuable tool for studying a given installation and hookup of its equipment**

# Centrifugal-pump and system curves

Unlike positive-displacement pumps (rotary and reciprocating), a centrifugal pump operated at constant speed delivers any capacity from zero to a maximum, depending on head, design and suction conditions. Characteristic curves, *above*, show interrelation of head, capacity, power and efficiency, for a specific impeller and casing.

It is usual to plot head, power and efficiency against capacity at constant speed, as above. But in special cases it is possible to plot any three variables against a fourth.

**Head-capacity curve,** labeled *H-Q*, shows relation between capacity and total head, and may be rising, drooping, steep or flat, depending on impeller type and design. At *A*, head is 144 ft, capacity 1200 gpm. At 120-ft head, *B*, the capacity rises to 1680 gpm.

**System-head curve,** *above*, is obtained by combining friction-head curve with static head and any pressure differences in pumping system. A friction-head curve is a plot of the relation between flow and friction in piping, valves

# Drives for centrifugal pumps

Probably every form of prime mover and power source, with some kind of transmission if needed, has been used for driving centrifugal pumps. Today, electric motors drive most centrifugals. But steam, gas and hydraulic turbines, gasoline, gas and diesel engines, are also used.

Factors affecting drive choice include pump and driver rpm, service conditions, pump characteristics, availability and cost of power, physical details of the installation.

**Driver speed** may be limited to a certain band, as in diesel and gas engines. This band may be above or below ideal pump speed for job conditions. Where pump runs continuously, a speed increaser or decreaser is usually warranted. For units used only occasionally, as in standby service, a compromise pump design is often chosen, saving cost and complication of a speed changer. There may be some sacrifice in pump performance, and a higher cost.

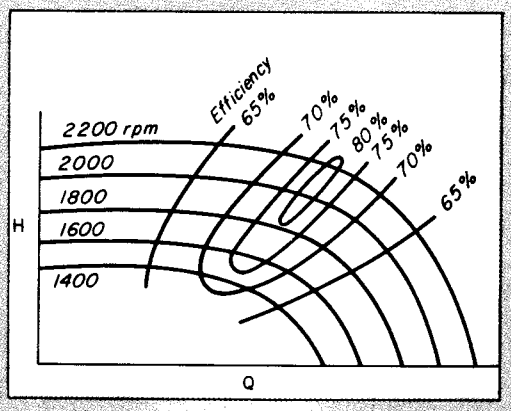
**Electric motors** for pump drive in the U. S. most often are full-voltage-starting ac units, though some dc motors find use. Generally, squirrel-cage motors are used, but synchronous and wound-rotor motors are also applied.

Recent development in *canned* and *axial-air-gap* sealed motors are almost certain to have a major influence in design of future small pumps. With some canned motors, p 101, straight-through flow is obtained, considerably simplifying piping connections. Axial air-gap motors shrink to almost pancake thickness, allowing easy installation and care. Both are leakproof, important in many process jobs.

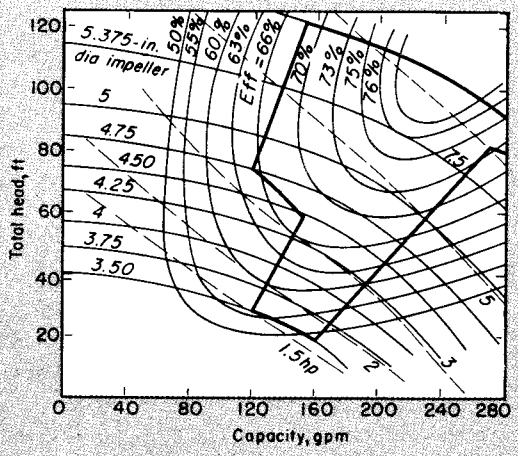
**Canned motors** appear to have a bright future in process and atomic-energy applications handling water at high temperatures and pressures. They also handle liquid metals.

The *electromagnetic* pump has no conventional driver. Instead, in the Faraday type, a heavy current is made to flow through the fluid (liquid metal), current entering the pipe wall through a brazed joint. Thus we're at the stage where raw energy, applied directly to the liquid, moves it from one point to another. In effect, we've bypassed one step present in pumping from earliest times—conversion of one form of energy into another in an impeller, piston, gears, etc.

**Starting torque.** Returning to today's more conventional practice, we find that normal-starting-torque motors are entirely adequate for starting centrifugals, even with discharge valve open. Starting torque from rest seldom exceeds




**VARIABLE-SPEED** head-capacity curves correlate head, rpm, efficiency and the capacity of the pump




**PUMP CHARACTERISTICS** when impeller diameter is varied within same casing find much practical use

and fittings in suction and discharge lines. Since friction head varies roughly as the square of the flow, a plot of it is usually parabolic. Static head is difference in elevation between liquid levels of suction and discharge.

**Superimposing** the pump $H$-$Q$ curve on the system-head curve gives point $A$, the head and capacity at which the pump operates in that particular piping system.

Where a pump runs at more than one speed, a plot like that above shows complete performance for a given suction lift. To obtain this chart, $H$-$Q$ curves are drawn for the speeds being considered. Then curves of points having the same efficiency are superimposed. These constant-efficiency curves, also called *isoefficiency* and *oak-leaf* curves, permit finding the required speed and the efficiency for any head-capacity condition.

**Impeller diameter.** Our first set of characteristic curves, *extreme left,* show performance for a specific impeller diameter, usually the maximum diameter. But impellers of more than one diameter can usually be fitted in a given casing. Curves above show performance of a given pump with impellers of various diameters. Heavy line encloses area of practical application of this particular design. Note how reduction in impeller diameter produces an effect similar to reduction in pump shaft speed in the previous curves. Tabulations of pump performance are made up by picking certain points from characteristic curves like those above.

15-20% of normal operating torque. It is usually highest in a sleeve-bearing pump that has been idle for some time.

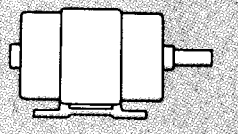
**Overloading** an electric motor is possible if pump horsepower increases with a change in capacity. But with a steam turbine, overloading is impossible because with a fixed throttle position, turbine speed is always a value such that pump torque equals turbine torque.

Internal-combustion engines may be rated for continuous load at rated speed, or for load at wide-open throttle, or for both. Most engines rated on continuous load will carry an overload. In any case, pump characteristics should be carefully studied before the driving engine is selected.

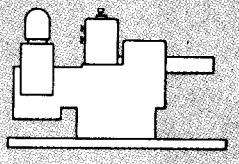
**Variable-speed operation** of centrifugals offers many advantages where varying capacity, head, or both, is needed. Since pump operating condition is fixed by crossing of its $H$-$Q$ curve with system-head curve, *above,* only way to alter operating condition of a constant-speed unit is to change system head by throttling. On many jobs it is more practical and economical to vary pump speed.

An economic study is usually needed to decide between variable and constant speed for given service. Power saving of variable speed may be more than offset by higher cost to be written off over unit's life. In boiler-feed service, allow for useful heat from power losses of throttling.

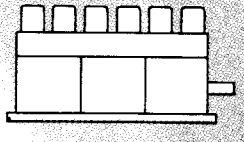
## POPULAR PUMP DRIVES



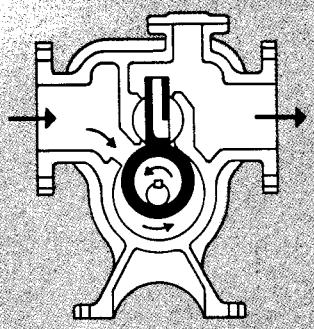
**Motors, by far the most common drive today, are well suited to almost all industrial pumping jobs**



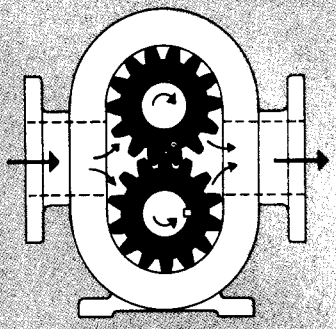
**Steam turbines offer simple speed variation, can sometimes be used to improve plant heat balance**



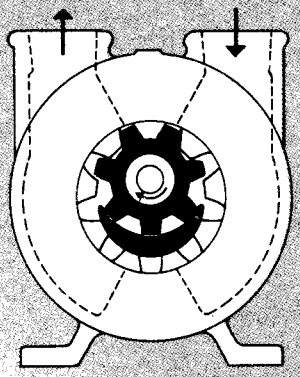
**Internal-combustion engine drive is particularly popular for isolated service, also temporary**



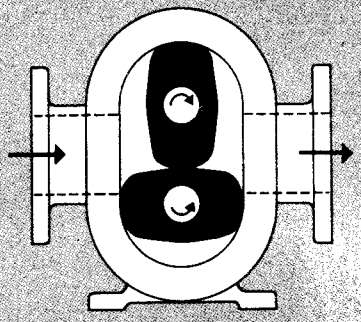
CAM-AND-PISTON



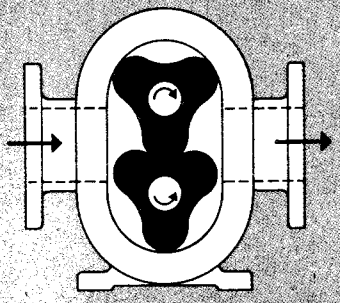
EXTERNAL-GEAR



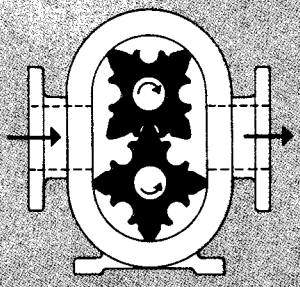
INTERNAL-GEAR



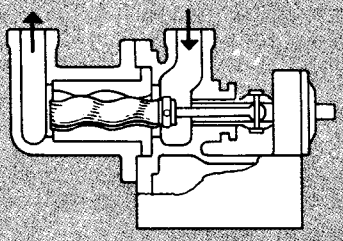
TWO-LOBE



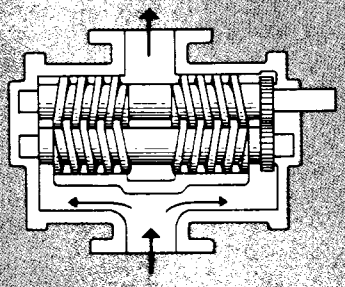
THREE-LOBE



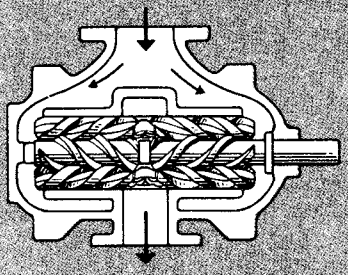
FOUR-LOBE



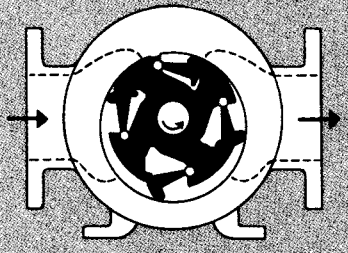
SINGLE-SCREW



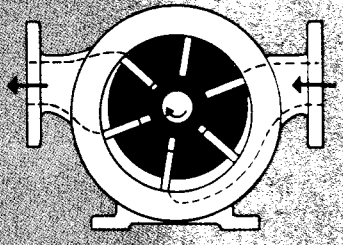
TWO-SCREW



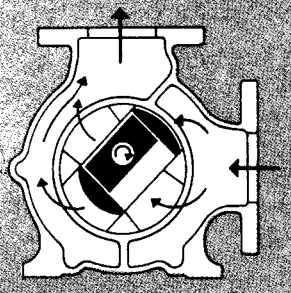
THREE-SCREW



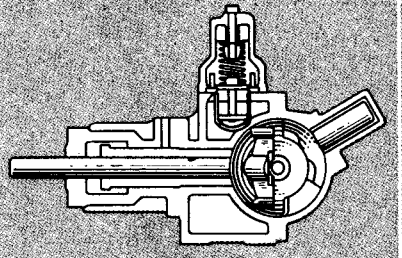
SWINGING-VANE



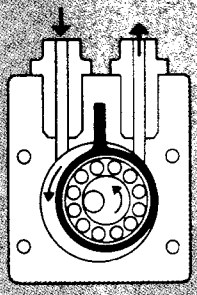
SLIDING-VANE



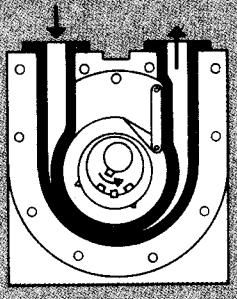
SHUTTLE-BLOCK



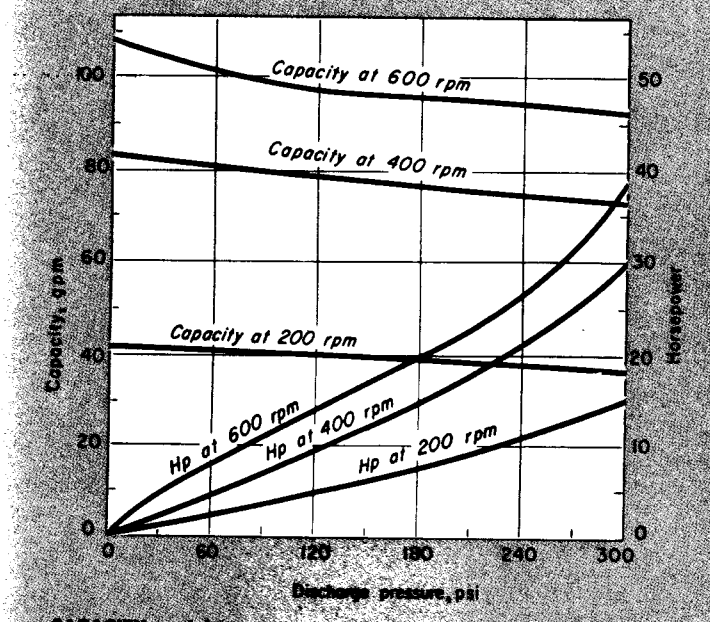
UNIVERSAL-JOINT



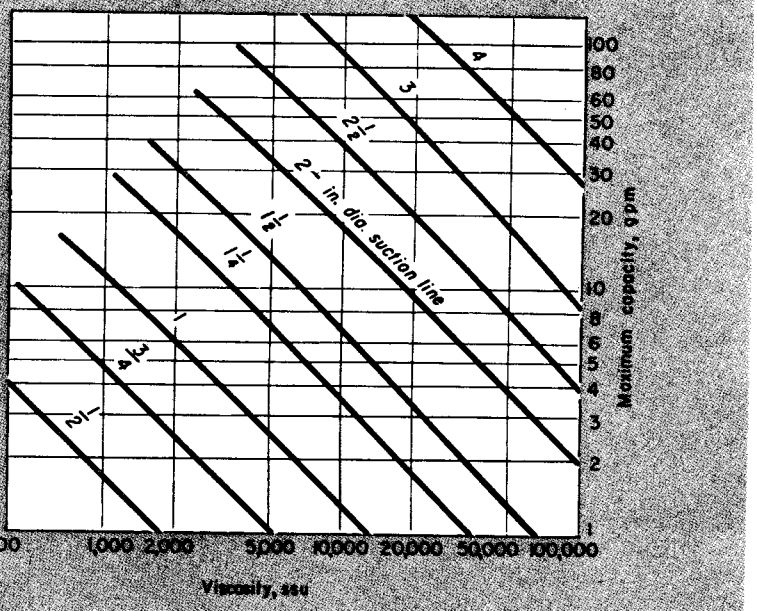
ECCENTRIC IN FLEXIBLE CHAMBER



FLEXIBLE-TUBE




CAPACITY and horsepower performance curves of a gear-type rotary pump handling heavy fuel oil. Note the flat *H-Q* curves




RECOMMENDED SIZE of suction piping for viscous liquids in 10 ft of straight pipe with two elbows and one gate valve

# Rotary pumps

Rotary pumps, usually positive-displacement units, consist of a fixed casing containing gears, vanes, pistons, cams, segments, screws, etc, operating with minimum clearance. Instead of "throwing" liquid as in a centrifugal, rotaries trap it, pushing it around the closed casing, much like reciprocating pumps. But unlike a piston pump, a rotary discharges a smooth flow.

Fifteen designs, *left,* illustrate a few of the devices chosen to move fluids from one point to another. Often thought of as viscous-liquid pumps, rotaries are by no means confined to this service alone. They'll handle any liquids from A to Z, if free of hard solids. And hard solids can be handled if steam jacketing will melt them. As with centrifugals, materials and drives vary with job, liquid, etc.

**Cam-and-piston pumps,** also called rotary-plunger type, consist of an eccentric with a slotted arm at its top. Shaft rotation causes eccentric to trap liquid in casing, discharges it through slot to outlet.

**External-gear pumps** are the simplest rotary type. Liquid first fills the spaces between gear teeth as they separate on suction side, is then carried around and squeezed out as the teeth mesh. Gears may have spur, single- or double-helical teeth. Some designs have drilled idler to cut internal thrust.

**Internal-gear pumps** have one rotor with internally cut teeth meshing with an externally cut gear idler. Crescent-shaped partition, to prevent liquid from passing back to suction side, may or may not be used.

**Lobular pumps** resemble the gear-type in action, have two or more rotors cut with two, three, four or more lobes on each rotor, synchronized for positive rotation by external gears.

**Single-screw pumps** have a spiraled rotor turning eccentrically in an internal-helix stator or liner. Rotor is metal while helix is hard or soft rubber.

**Two- and three-screw pumps** have one or two idlers, respectively. Flow is between the screw threads along the axis of the screws. Opposed screws may be used to eliminate end thrust.

**Swinging-vane pumps** have a series of hinged vanes which swing out as the rotor turns, trapping liquid and forcing it out the discharge pipe.

**Sliding-vane pumps** use vanes that are thrown against casing bore when rotor turns. Liquid trapped between two vanes is carried around and forced out the discharge.

**Shuttle-block pump** has a cylindrical rotor turning in a concentric casing. In the rotor is a shuttle block and piston reciprocated by an eccentrically located idler pin, producing suction and discharge.

**Universal-joint pump** has a stub shaft in free end of rotor supported in a bearing at about 30 deg with the horizontal. Opposite end of rotor is fixed to drive shaft. When rotor revolves, four sets of flat surfaces open and close for a pumping action of four discharges per revolution.

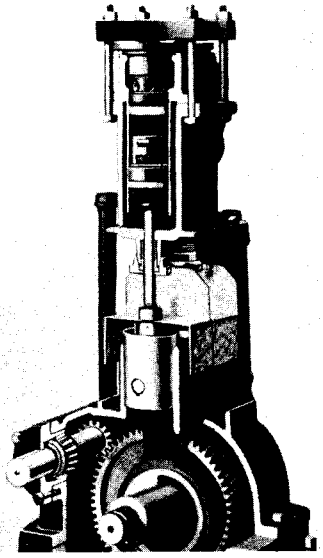
**Eccentric in flexible chamber** produces pumping action by squeezing the flexible member against pump housing to force liquid out discharge.

**Flexible-tube pump** has a rubber tube squeezed by a compression ring on an adjustable eccentric. Pumps of this design are built single- and 2-stage.

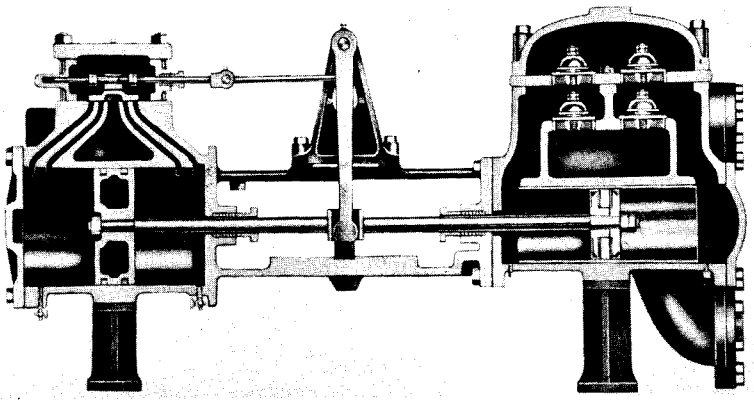
Characteristic curves, *above left,* for a typical rotary gear pump show the flat *H-Q* relation obtainable. Displacement of a rotary varies directly as speed, except as capacity may be affected by viscosity and other factors. Thick liquids may limit pump capacity at higher speeds because they can't flow into casing fast enough.

Slip or loss in capacity through clearances between the casing and rotating element, assuming a constant viscosity, varies as pressure increases. For example, in above curves, capacity at 0 discharge pressure is 108 gpm. But at 300 psi and same speed, capacity is 92 gpm. Difference is slip.

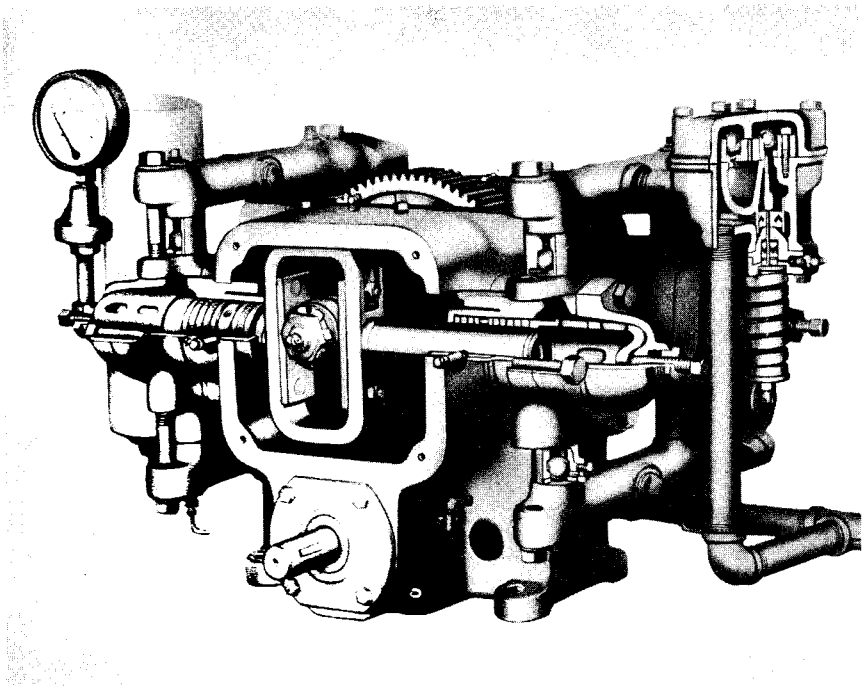
Power input to a rotary increases with liquid viscosity; efficiency decreases. This is true, of course, with other classes of pumps. But since rotaries find wide use for viscous liquids, it is wise to use the chart, *above right,* for sizing suction lines to prevent excessive friction loss.



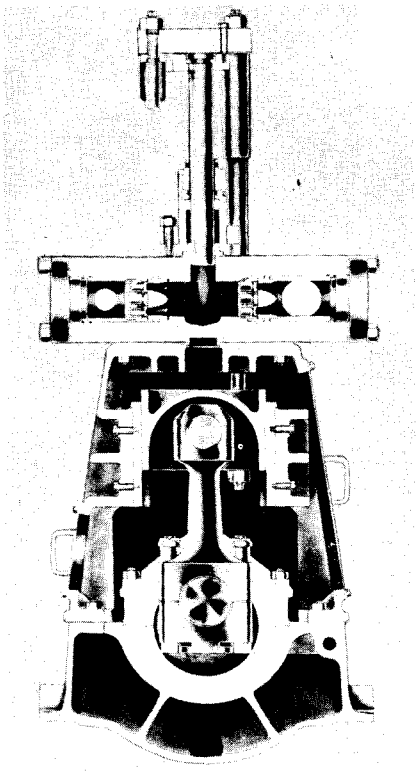
**SINGLE-ACTING** vertical-type power pump has pinion shaft for driving crankshaft



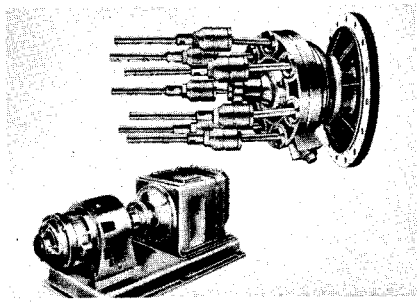
**DIRECT-ACTING** horizontal duplex piston pump. Steam end is at left, liquid end is at right. Piston-rod motion shifts steam valve for admission and exhaust of the steam



**QUADRUPLEX** horizontal-plunger power pump for high pressures is motor driven through pinion and gear. Each Scotch yoke drives two plungers. Pump valves are the ball type



**INVERTED** triplex vertical-plunger power pump for high-pressure job applications



**ROTARY-PLUNGER** single-acting pump unit has five or seven plungers in a circle

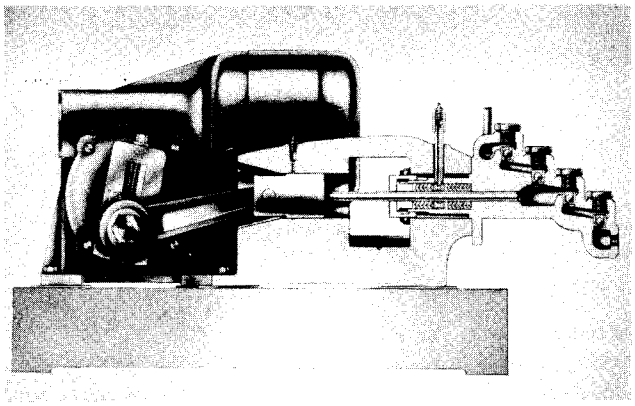
# Reciprocating pumps

The 13 pumps on these two pages are but a few of the many reciprocating types in regular use today. But you will find shown here most of the major designs.

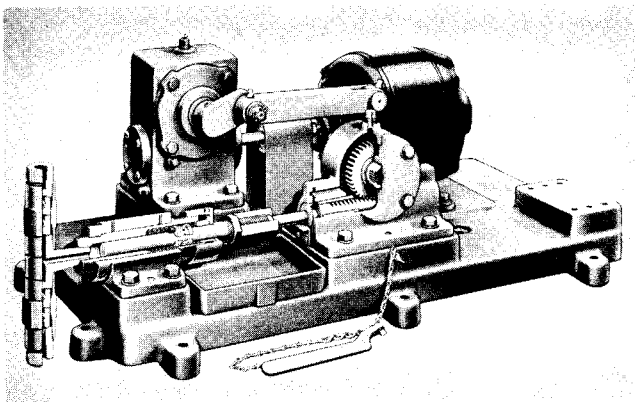
Reciprocating pumps, unlike centrifugals, p 80, are more often classed according to type, rather than use. Perhaps this is because their ultimate use is less clearly defined than for centrifugal pumps. While certain applications for this type, like fuel-oil pumping, are declining, others, like boiler and chemical feeding, are rising.

Biggest recent developments are in non-geared higher speed power pumps — both large and small units. Adjustable displacement pumps, also called metering and proportioning or controlled-volume, are being improved every year to give wider capacity ranges, greater accuracy, easier control.

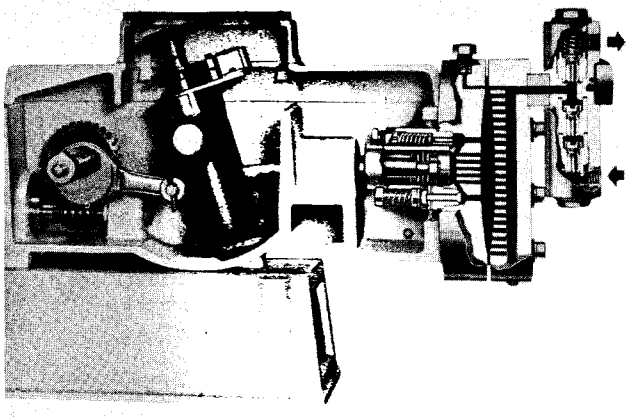
Power pumps, always of importance in the marine field for boiler feed are finding some new berths in stationary plants for the same service where loads justify them. And if pressures in superpressure plants rise, it is likely that power-type reciprocating pumps will be used for boiler feed. Of course, much depends on new developments in the design of centrifugal pumps.



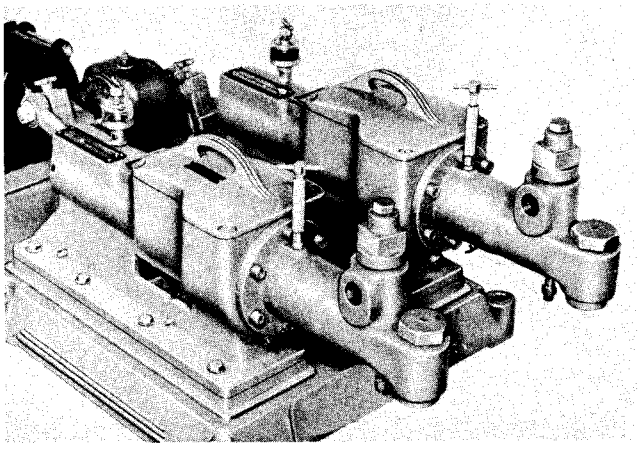
**CONTROLLED-VOLUME** plunger pump has screw adjustment of stroke length. Change of crankpin position alters capacity of pump



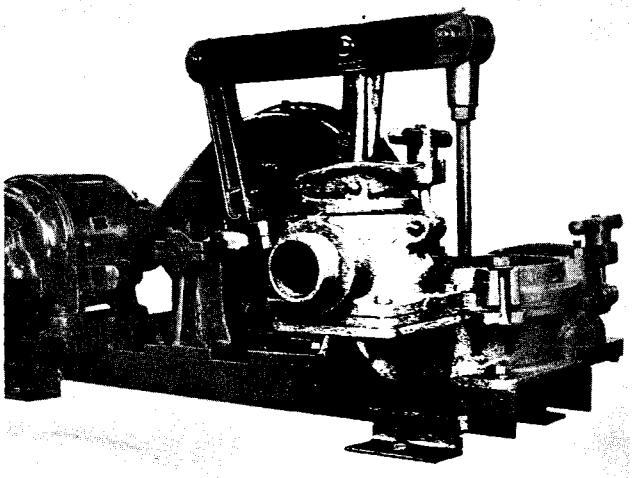
**METERING** and proportioning plunger pump has lost-motion type of coupling for adjusting stroke length and capacity of pump



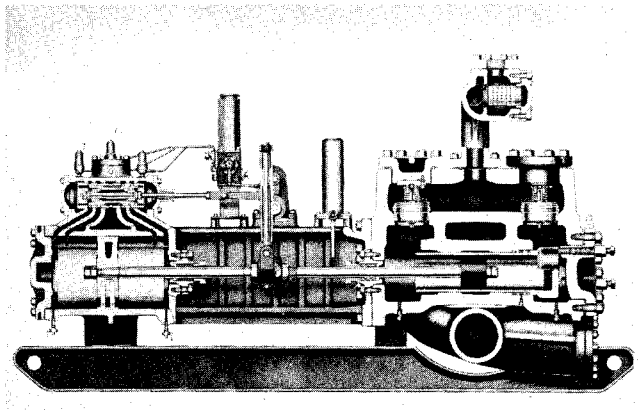
**PISTON-DIAPHRAGM** unit for controlled-volume pumping has oil for actuation of diaphragm which pumps the liquid handled



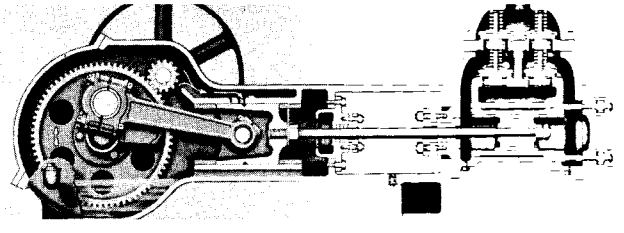
**DUPLEX** plunger-type feeder pump has micrometer adjustment of stroke length by means of variation of the crankpin position



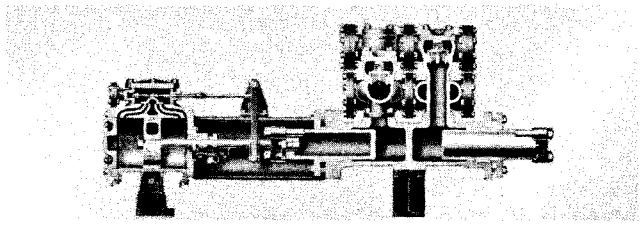
**DIAPHRAGM** pump with ball suction and discharge valves is built with stationary or movable base, is motor driven through beam



**DUPLEX STEAM** slush pump has divided-cylinder pot-type liquid end with suction manifold at the bottom of the liquid cylinder

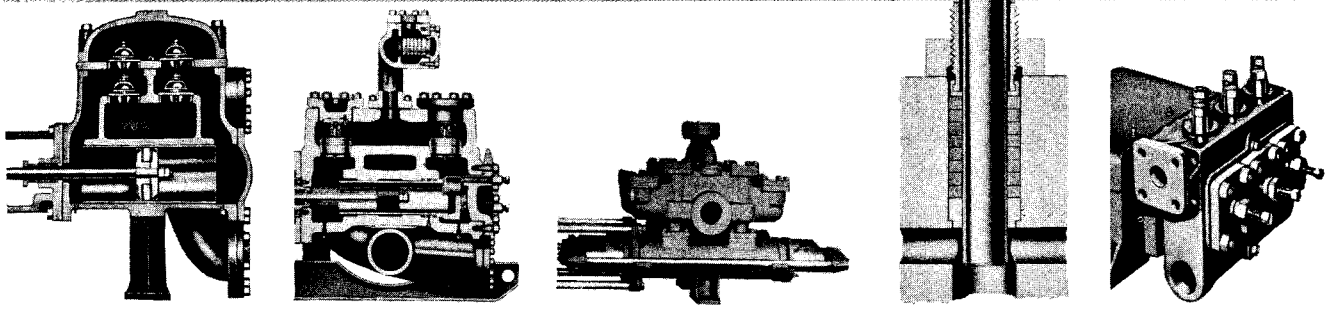


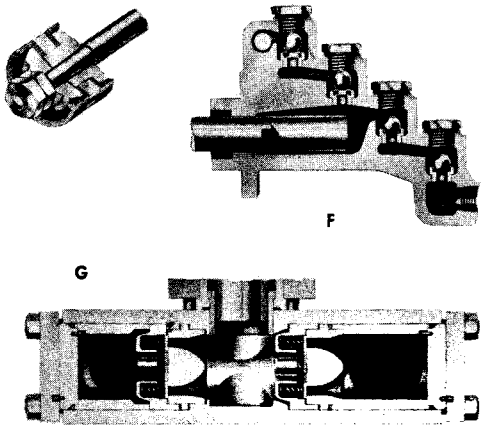
**HORIZONTAL SIMPLEX** power pump is driven by pinion geared to crankshaft, has disk-type suction, discharge valves, air dome



**HORIZONTAL DUPLEX** outside-end-packed pot-valve-type plunger pump: the plungers shown are attached together by the tie rods

## Liquid ends for direct-acting and power pumps




Reciprocating-pump liquid ends are built in a large number of designs for various liquids, service conditions and pressures. Shown above are a few typical arrangements for modern pumps.

Direct-acting steam pump, *A*, often has *valve-plate* liquid end with removable discharge-valve decks. Cup-type packing for liquid piston is also shown. *Valve-pot* type, *B*, has valve chambers closed by individual covers. *Outside-packed* plunger pump, *C*, has its valves in pots—all packing leakage is external where it can be seen.

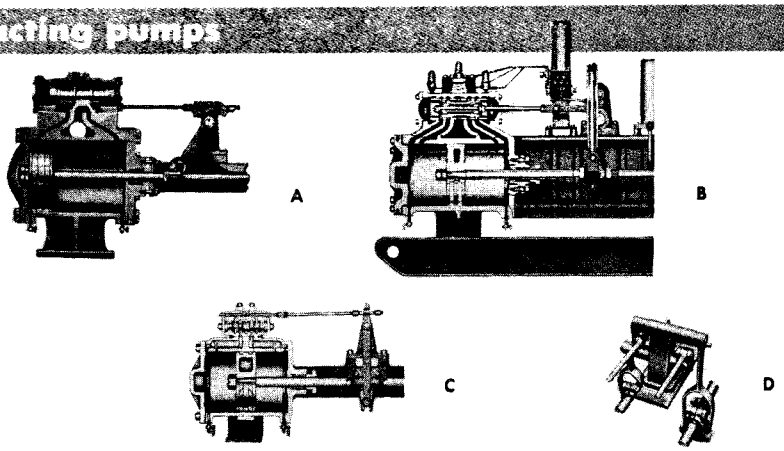
Vertical power pump, *D*, has plunger packing at cylinder top, while horizontal triplex pump, *E*, has it in the usual location with valves above and below plunger. At *F*, valves are in step arrangement. Another design for a vertical triplex pump appears at *G*. Liquid-end design is a function of pressure developed, liquid handled, capacity, etc.

## Steam ends of direct-acting pumps

Flat or 'D' slide valves find use for steam pressures of 200 psi and less Balanced piston valves are common in large high-pressure pumps.

*Flat valve, A,* is thrown by auxiliary piston. Motion is regular and positive. *Balanced-piston valve, B,* runs in sleeve, has minimum friction, long life. *C* is another *balanced-piston* valve.

Typical steam-valve linkage, *D*, connects to rod. Steam-end design of vertical pumps resembles those shown.

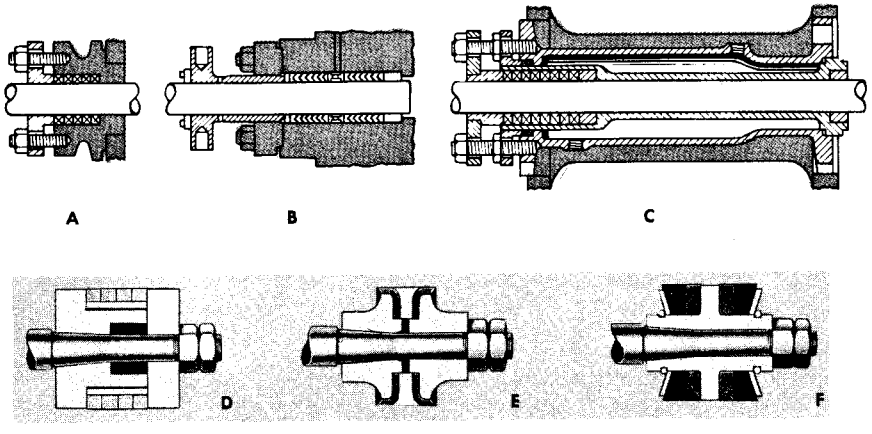



## Packing

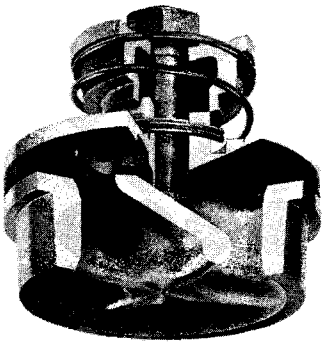
Packing is any material used to control leakage between a moving and stationary part in a pump. Flexible, and usually soft, it is expendable.

Simple piston-rod stuffing box, *A,* has several rings of square packing. On small rods a single nut surrounds gland, instead of studs shown. *Chevron* packing, *B,* is often used. Sketch shows plunger of high-pressure pump. *C* is a jacketed stuffing box.

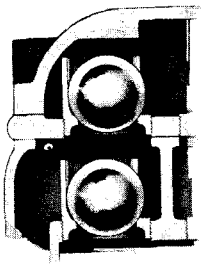
Piston packing takes many forms. *Duck-packed* piston, *D,* is for bronze-fitted general-service pump. *Cup* packing, *E,* is standard for oil pumps. *Solid rubber rings, F,* are also popular.



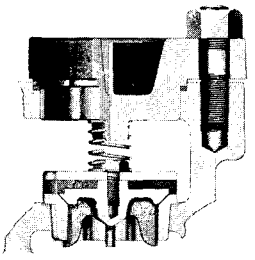
## Liquid valves for direct-acting and power pumps



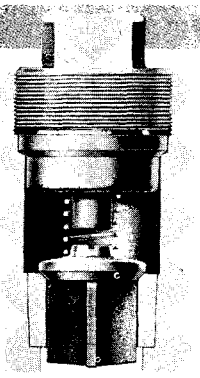
A



B



C

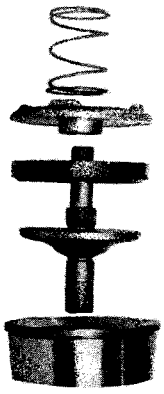


D

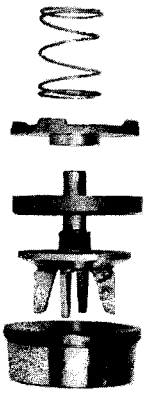
As a general rule, stem-guided disk valves are used for low-pressure jobs, wing-guided (flat- or bevel-faced) for moderate pressures, and bevel-faced wing for high pressures. But much depends on liquid, etc.

*Flat disk, A,* has inclined ribs in seat to direct liquid so it rotates disk slightly at each stroke. *Ball valve, B,* often finds use where free opening for thick liquid is desired. Cage guides ball during its rise and fall. Seat is circular and completely open. *Wing-guided* valve, *C,* for thick gritty liquids, can be fitted with renewable rubber inserts for wings. Another design, *D,* for high-pressure clear liquids, has renewable seats.

*Low-pressure* valve, *E,* and *high-pressure* valve, *F,* for thick liquids are alloy-steel with synthetic inserts for all ordinary services. Special materials are used where corrosive liquids are to be handled. Double-ported ring-type valves, *G,* p 92, are popular in large power pumps.

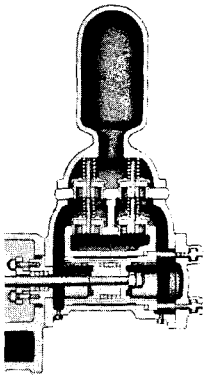


E



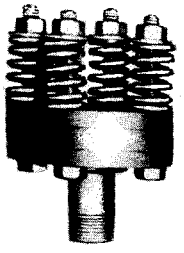
F

## Cushion chambers and pressure alleviators



A

B

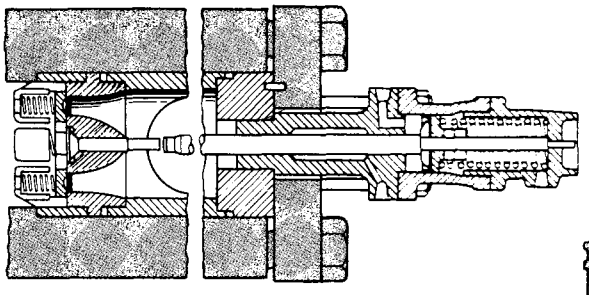


C

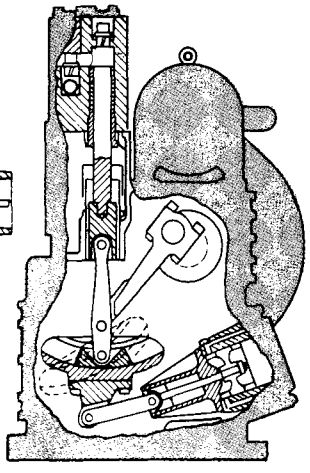
*Suction* and *discharge cushion chambers* smooth liquid flow. Discharge chamber, *A,* is often built as part of pump while suction chamber may be part of pump or in adjacent piping.

Pressure alleviators, *B* and *C,* find use with high-pressure power pumps to absorb shock from sudden stopping of liquid. They usually consist of a spring-loaded plunger operating in a stuffingbox. Liquid does not escape from piping system during surges.

## Variable capacity



A

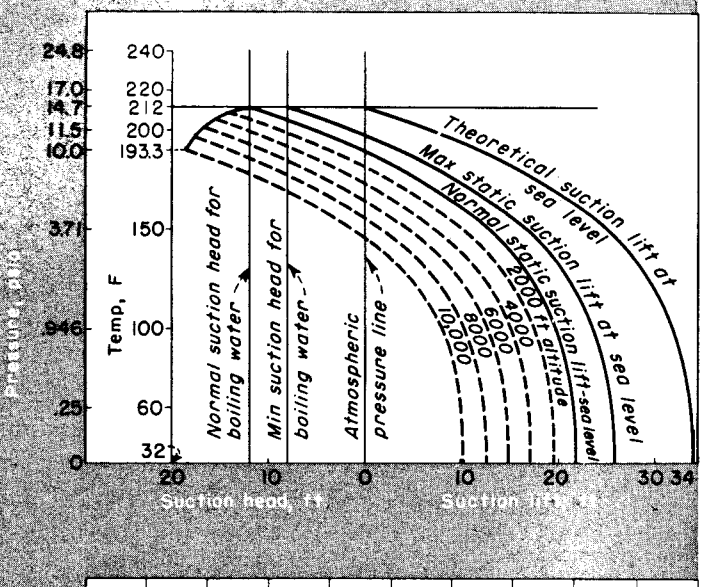


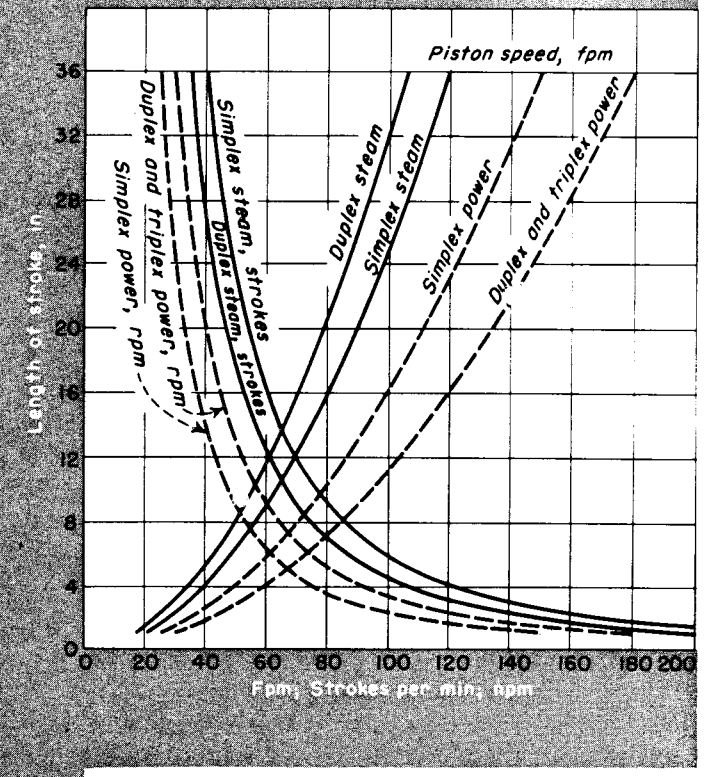
B

There seems no end to devices for varying capacity of small reciprocating pumps. A few appear on pp 90-91. For large power pumps, however, not so many variations exist perhaps because of the lesser number of designs.

*Suction-valve unloader, A,* gives a quick but gradual reduction in liquid delivery from full to zero flow in not more than one-half revolution of pump. It increases liquid delivery in same way, is pneumatically actuated.

*Stroke-transformer, B,* can automatically or manually vary plunger motion from zero to maximum stroke. Output is infinitely controllable.




## Suction lift

Recommended total suction lift is 22 ft for slow-speed reciprocating pumps handling cold water at sea level. High-speed pumps usually aren't capable of lifts that high. Curves, *left,* show effect of altitude and temperature on lift of a 6x4x6-in. valve-plate-design duplex direct-acting pump.

**Maximum theoretical suction lift** of a pump is 34 ft. of cold water at sea level. Difference between this and the practical lift represents losses in valves, pipe friction, velocity head and various entrances in the system.

Other factors affecting practical lift include pump type, and design of suction valves, pistons, plungers, suction passages, liquid vapor pressure. So limits shown in curves should be taken only as illustrative of one particular design.

## Capacity and speed

Reciprocating pumps don't suck in liquids; they reduce pressure in the suction chamber and external pressure, usually atmospheric, pushes liquid into the pump. For any pump with a given size suction line, capacity or maximum speed is fixed by existing *net positive suction head* (npsh).

As speed of a reciprocating pump rises, so does its capacity, provided nothing interferes with flow into and out of pump. Curves, *left,* show basic speeds for direct-acting and power pumps. For former, speed is expressed in feet per minute piston motion; for latter, either as piston speed or rpm.

**Viscosity and temperature** of liquid pumped also influence maximum pump speed and capacity. Thus, as viscosity of liquid changes from 250 to 5000 ssu (table at left) pump speed falls from rated to about 65% of rated. As temperature rises from 70 to 250 F. we have a similar speed decrease to 62% of rated.

Semi-solids, like acid sludge, molasses and syrup, are handled in reciprocating pumps designed to run without a suction valve. Either ball or disk discharge valves are used.

When considering a given pump, check with its maker to determine exact effects of viscosity, npsh, temperature and design on capacity. Generalizations, while helpful guides, must not be used too freely. Table, *left,* summarizes speed correction factors for viscosity and temperature recommended by Hydraulic Institute. To use, simply multiply rated speed by percentage reduction, expressed as a decimal.

### Speed correction factors

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Liquid viscosity, ssu | 250 | 500 | 1000 | 2000 | 3000 | 4000 | 5000 |
| Speed reduction, % | 0 | 4 | 11 | 20 | 26 | 30 | 35 |
| Liquid temperature, F | 70 | 80 | 100 | 125 | 150 | 200 | 250 |
| Speed reduction, % | 0 | 9 | 18 | 25 | 29 | 34 | 38 |

### Approximate efficiencies — direct-acting pumps

| Stroke, in. | 5 | 8 | 10 | 20 | 30 | 40 | 50 |
|---|---|---|---|---|---|---|---|
| Crank-and-flywheel pump | | | | 87 | 88 | 90 | 92 |
| Piston pump | 60 | 70 | 74 | 84 | 86 | 88 | 90 |
| High-pressure pump | 55 | 64 | 67 | 76 | 78 | 80 | 81 |

### Approximate efficiencies — power pumps

| Water hp | 3 | 5 | 10 | 20 | 30 | 50 | 75 | 100 | 200 |
|---|---|---|---|---|---|---|---|---|---|
| Efficiency, % | 55 | 65 | 72 | 77 | 80 | 83 | 85 | 86 | 88 |

## Efficiency

As with any machine, efficiency of a reciprocating pump varies with size, design, application, etc. Though it is risky to generalize about pump efficiencies, tables, *left,* summarize typical ranges for direct-acting and power pumps.

**Leakage** past pistons, stuffing boxes and valves, expressed in percentage of liquid - piston displacement is *slip,* and equals 1— volumetric efficiency, expressed as a decimal. Slip in new pumps is about 2%; in some low-head designs it may be as low as 0.5%. Where inertia of liquid column is high slip may be negative.

**Efficiency** given in the tables is sometimes referred to as *gross* efficiency for direct-acting pumps, and is the ratio of pump output in water or liquid horsepower to the power input. Latter is indicated horsepower of a direct - acting steam pump or brake horsepower of a power pump.

While pump efficiency is always of interest, its relative importance depends much on pump capacity, service, etc.

# Liquid-end characteristics

Discharge of centrifugals and most rotaries is steady. But with reciprocating pumps it pulsates, character depending on pump type and whether or not it has a cushion chamber.

**Simplex direct-acting** steam pumps at normal speed have a discharge curve like that at right. The flow is steady until end of stroke, where piston stops and reverses. Without an air cushion, flow theoretically ceases when the piston stops. But cushion prevents this, giving loops shown.

**Duplex direct-acting** pump, *right,* has discharge of one cylinder displaced half a stroke from that of other. The two add together to give solid line with twice as many valleys as simplex, but low points are never below those of simplex.

**Power-pump discharge** curves, *right,* take form of sine waves because pistons or plungers are crank - driven. Discharge flow doesn't change as abruptly as with direct-acting pumps.

**Simplex double-acting** power pump for which curve is plotted has maximum flow rate 60% above average; minimum below average is 100%. This means that at a point during each pumping cycle, flow from pump is zero. But flow from the discharge line may be nearly constant, depending on job; physical conditions and piping layout.

**Duplex double-acting** power pump gives us the second curve shown, *right.* Here maximum flow rate is 26.7% above average; minimum is 21.6% below average. Thus, we always have flow in discharge pipe while pump is running.

**Triplex single-acting** pump further smooths discharge curve, as shown. Maximum flow rate above average here is 6.64%; minimum below is 18.4%. With any reciprocating pump, difference between maximum discharge and average quantity is stored in cushion chamber until discharge drops below average.

**Quintuplex and septuplex** power pumps smooth the discharge curve even more, to give practically constant discharge-line flow. Ultimate test of discharge-curve suitability is the job itself. Large pulsations may be of minor importance in one installation, yet in another they may be the major consideration.

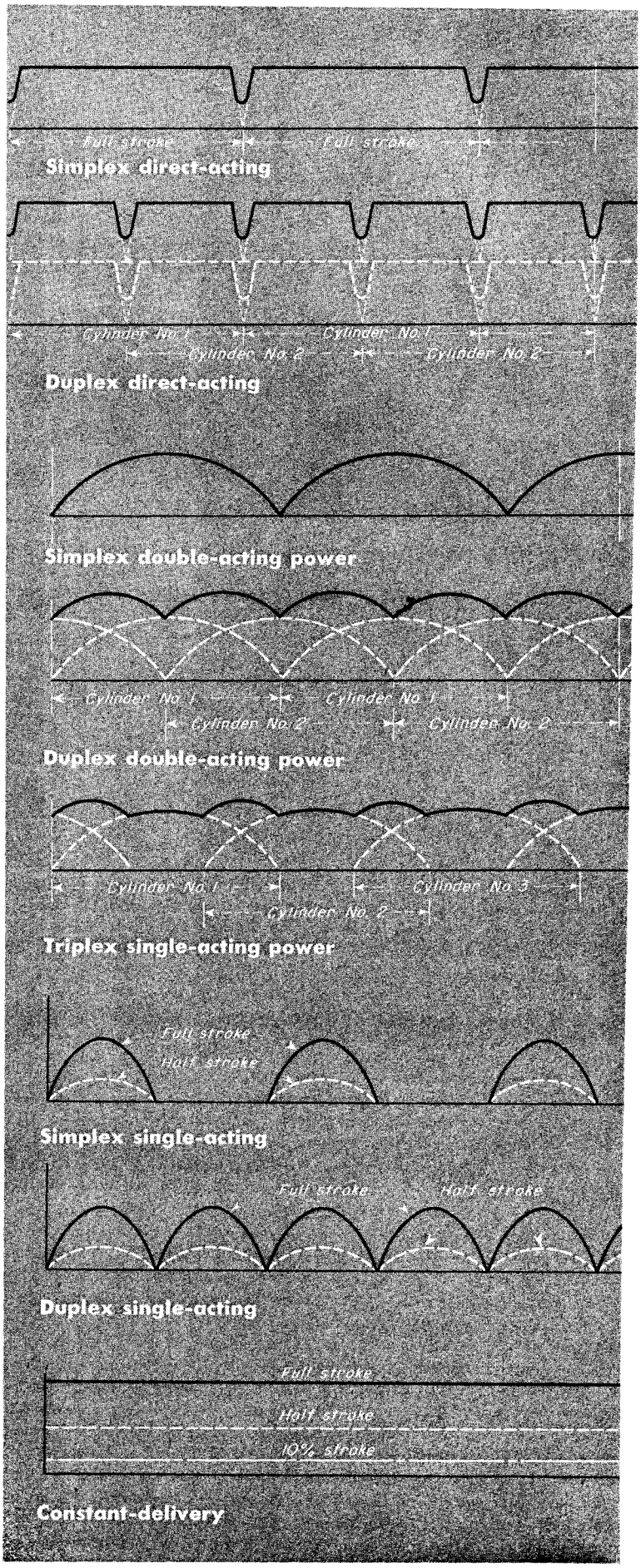
**Variable-capacity pumps** resemble, to a certain extent, their bigger brothers when it comes to the discharge curve. But the fact that capacity can be changed as desired alters the appearance of the curves somewhat.

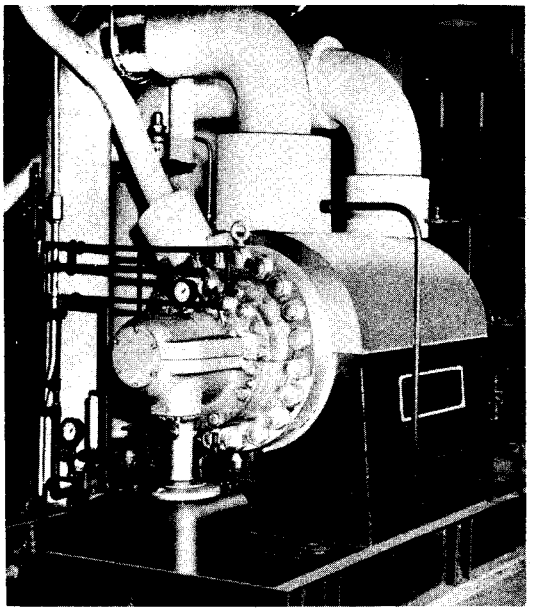
**Simplex single-acting** pump has pulsating flow shown at right, with no discharge during suction. When the capacity is decreased, the sine-type curve becomes flatter, as shown.

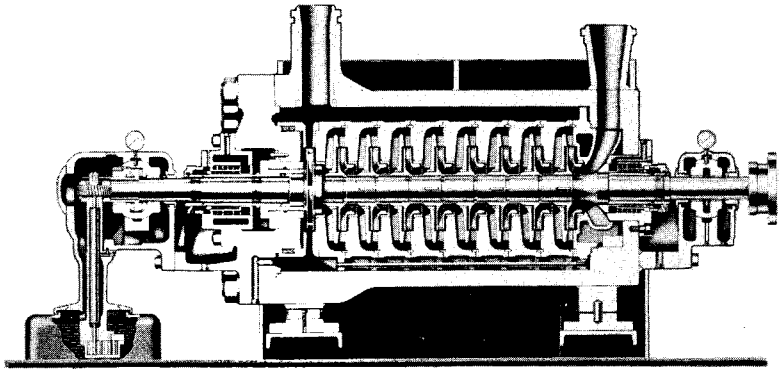
**Duplex single-acting** designs deliver twice as much liquid, and have discharge curves similar to simplex units. But when one piston stops delivering liquid, the other starts, if pistons are 180 deg apart, as shown at right. So we have no lengthy periods of zero flow from the pump.

Where constant delivery is desired without pulsation, a discharge curve like that at bottom right can be obtained by using a special design for this service. Note here how the curve is flat throughout, whether the pump runs at full stroke, half, or less.

Once again it is important to remember that the discharge curve of a reciprocating pump is not a measure of its efficiency, but simply a graphical representation of what is happening in the pump discharge. The final measure of the importance of the curve shape is the job requirements.

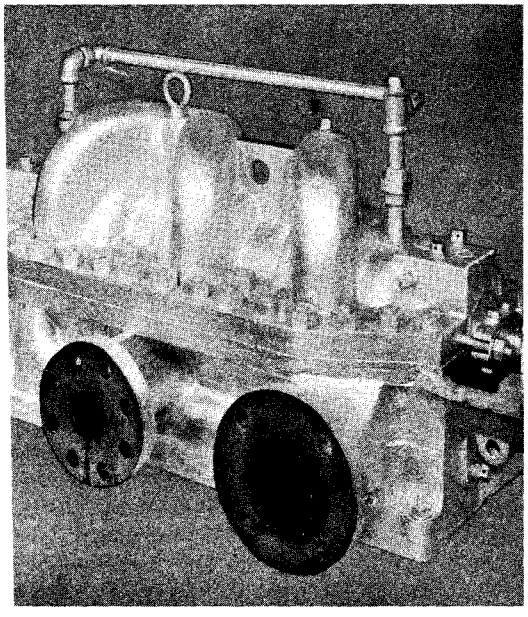


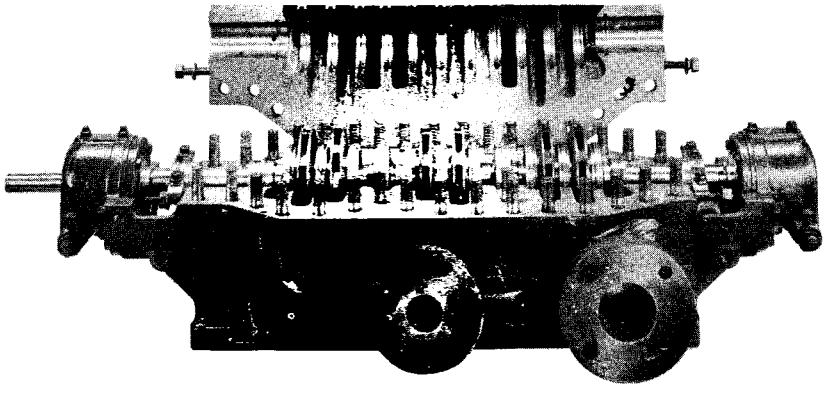




## High-pressure boiler feed

The modern double-case barrel-type centrifugal pump is today's answer for pressures approaching 6000 psi and temperatures to 1000 F. In the common 2600-psi range, units of this type run at about 3600 rpm, have up to 12 stages. The first superpressure plant uses two pumps of this type in series, with heaters between. Note how vertically split inner assembly is housed in casing.





## Medium- and high-pressure boiler feed

Horizontal split-case diffuser-type pumps with about six stages are common for 3600-rpm duty at pressures to 1600 psi. Some thinking today sees these units applied up to 2500 psi, but that is in the future. Design shown is 6-stage with back-to-back impellers in groups of two for better hydraulic balance. A big advantage of this type of pump is easy removal of top for maintenance.

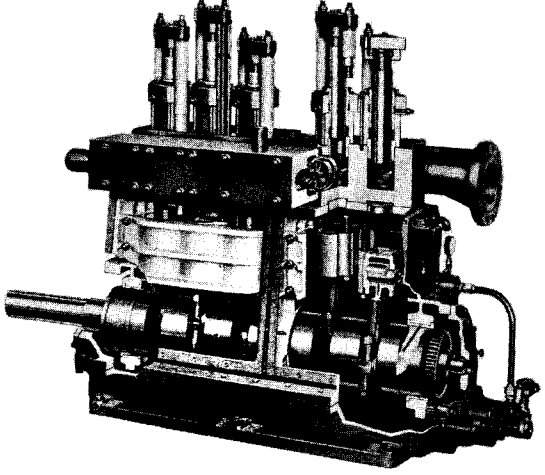
# Pump applications

Any attempt to list every possible application of pumps is almost certain to run aground because editors, being human, might overlook important jobs like pumping goldfish, apples, oranges, eggs and beer.

So these two pages, and the following four, give a necessarily selective cross section of pump classes and types *on the job.* There lies the ultimate goal of pump designers and builders—a product that performs a given service at the best over-all cost with minimum operating and maintenance needs. To secure these results the pump must be suited to the job, installed correctly, operated and maintained as the builder recommends. For now, let's take a quick look at application.

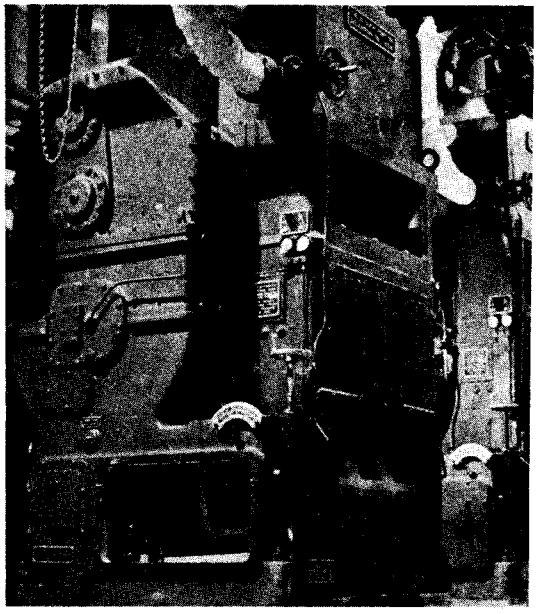
Pump class, type, drive and materials are among the major factors in unit selection. While generalizations are often dangerous, studies of a large number of modern installations show that industrial and service establishments throughout the U. S. use centrifugals for about 60% of their jobs, reciprocating for about 22%, rotary for about 12% and deepwell for about 6%. About 86% of the centrifugals have motor-drive, 44% of reciprocating, 96% of rotary and 95% of deepwell. Steam engines, turbines and internal-combustion engines drive about 13% of the centrifugals. Steam is outstanding for reciprocating units, driving almost half of those in use.

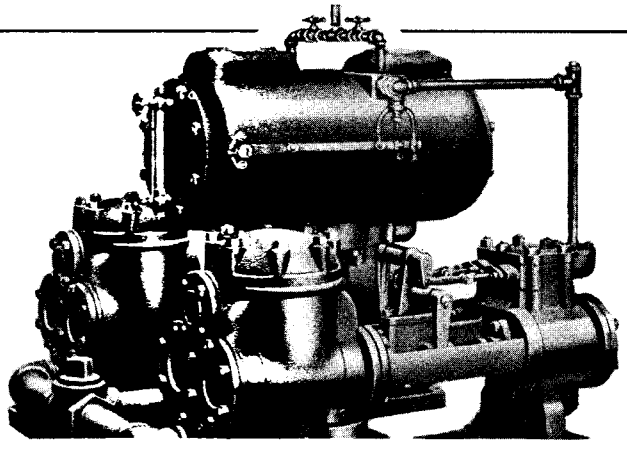
While these statistics are helpful from an over-all viewpoint, they serve merely as a guide to what industry is doing today. For help with a specific installation, the text and illustrations on these six pages will lead you through the maze of classes and types toward a sound answer.



## Power reciprocating for boiler feed

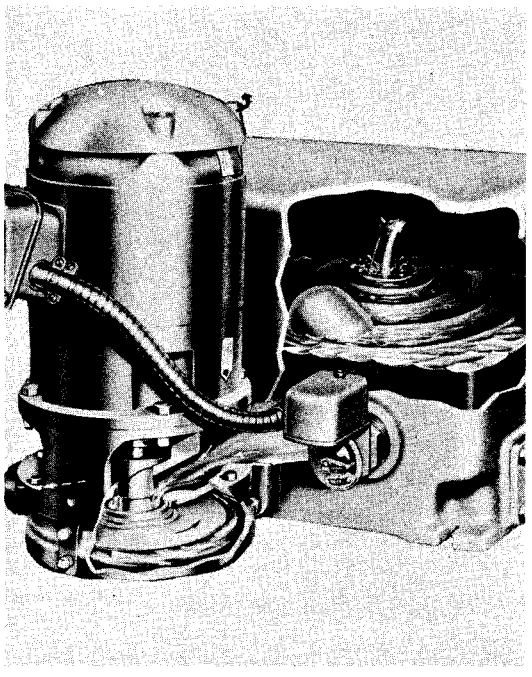
At pressures over about 250 psi where load is variable, power reciprocating pumps find application. They are also used for desuperheater feed in this pressure range. Vertical quintuplex units like that above are popular in feed service because they are easy to control automatically in stepless straight-line fashion from 0 to 100% of rated capacity. Use is now on the upswing.

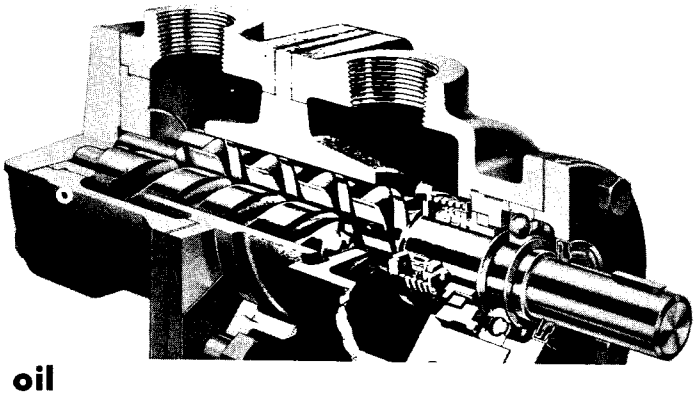




## Low-pressure boiler feed

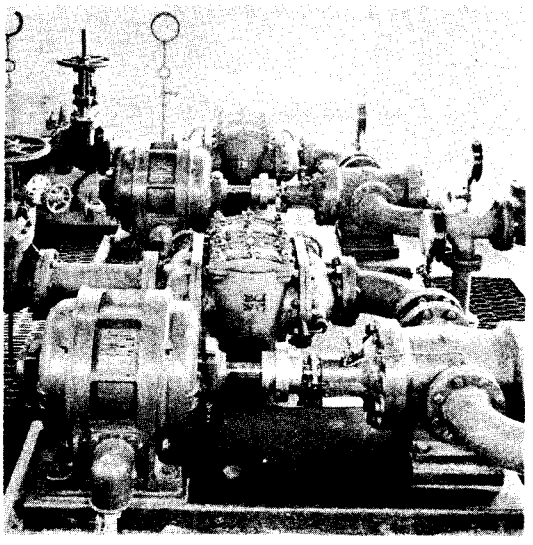
Direct-acting pumps, with or without receiver, find use in smaller low-pressure boiler installations. Simple, rugged and economical, they give outstanding service. Though not always classed as feed pumps, centrifugal condensation sets, *right,* are extremely popular in heating and similar installations. Compact and efficient, they handle wide temperature, pressure, capacity ranges.

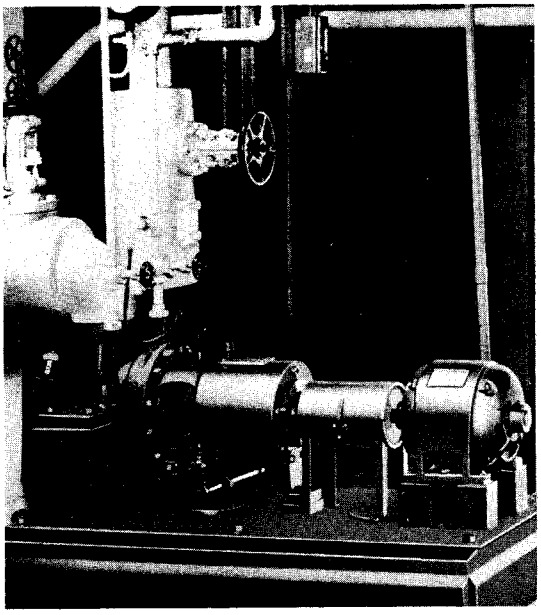


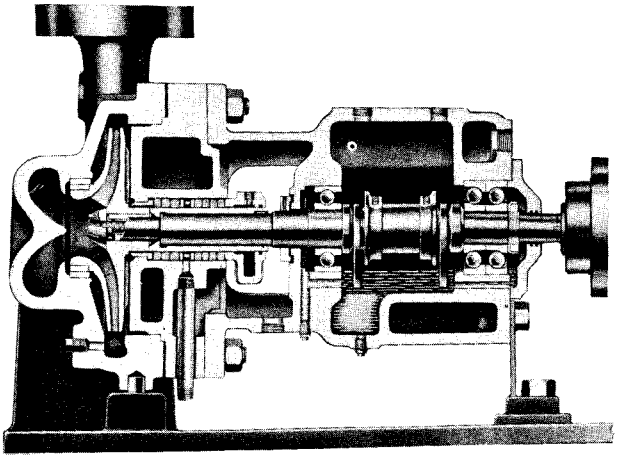


## Fuel oil

Screw and gear pumps are the modern units for fuel-oil pumping but direct-acting steam pumps still do the job in some plants. Screw pump shown handles up to 80 gpm at continuous pressures of 275 psig, intermittent to 325 psig. Pumps of this type find many other uses besides fuel-oil pumping, including lubrication, booster, circulating, governing and elevator jobs.

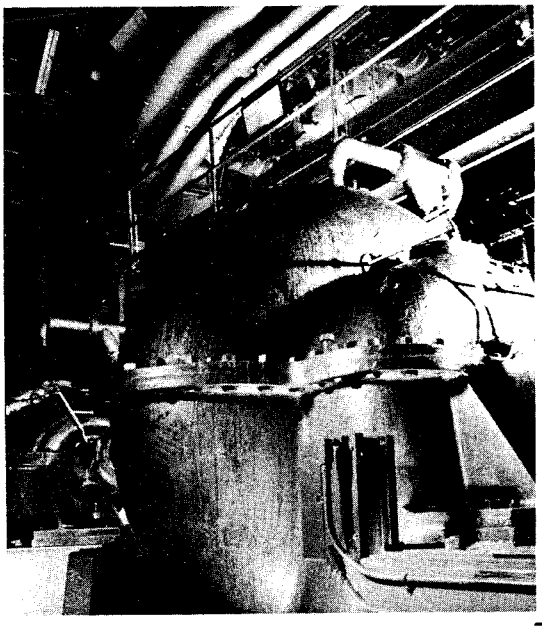


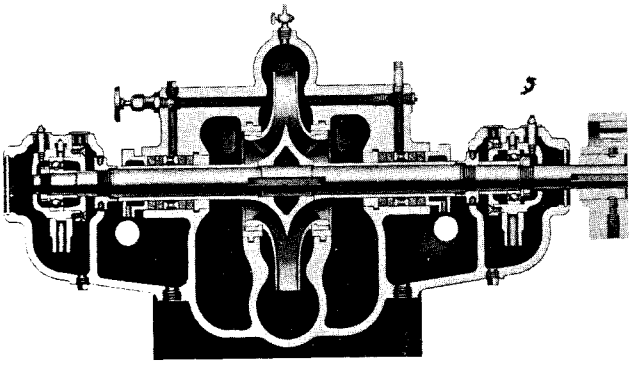




## Heater drains, condensate

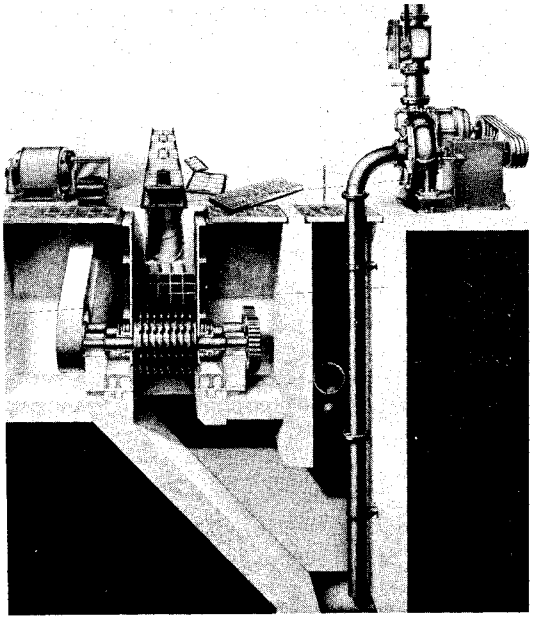
Handling condensate from hotwells, heater drains and other sources may impose severe operating conditions on a pump. In condenser service, suction head is low, liquid is near the boiling point, suction seal is a minimum and load changes wide. Usual centrifugal condensate pumps have one to four stages, special sealing and balancing features. Unit shown is single-stage.

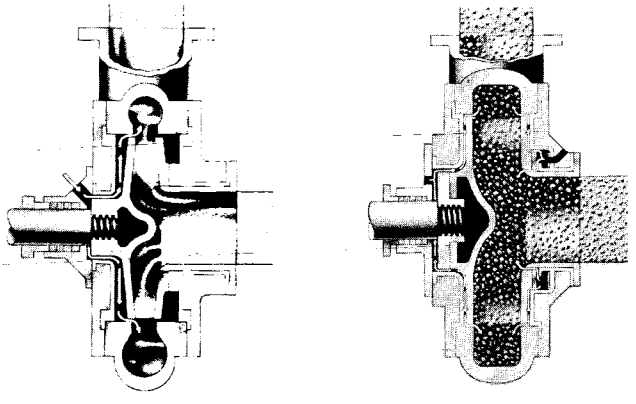




## Cooling water

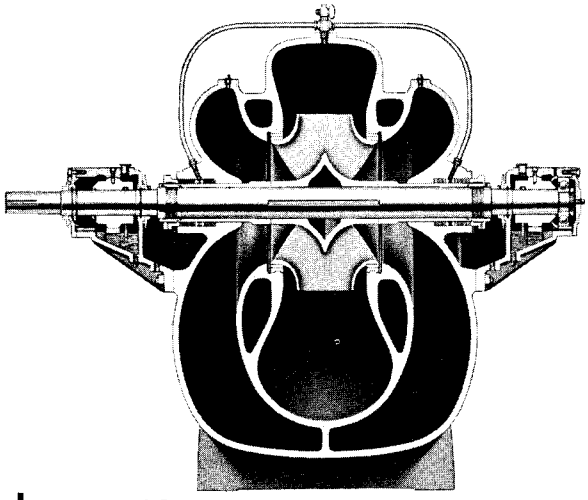
Whether tremendous, like the 55,000-gpm unit at left, or tiny as those on a small air conditioner, cooling-water pumps have some common traits. They are usually single-stage, standard-fitted, split-case. In the larger capacities they are often horizontal units, though many vertical designs are also used, both large and small. Their duty is seldom severe; operation is trouble-free.

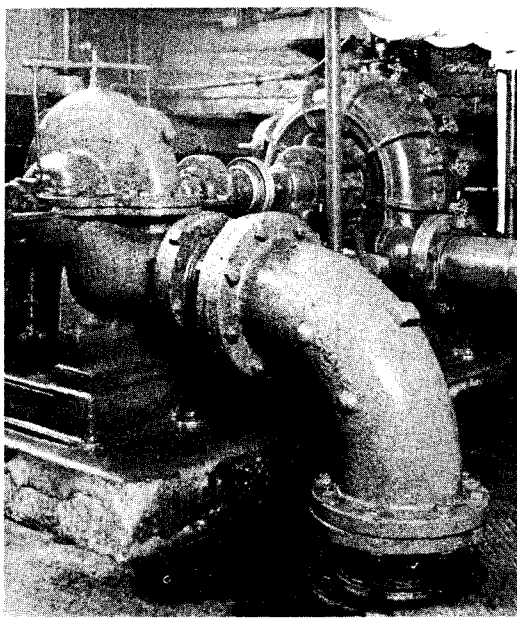




## Handling ash, abrasive solids

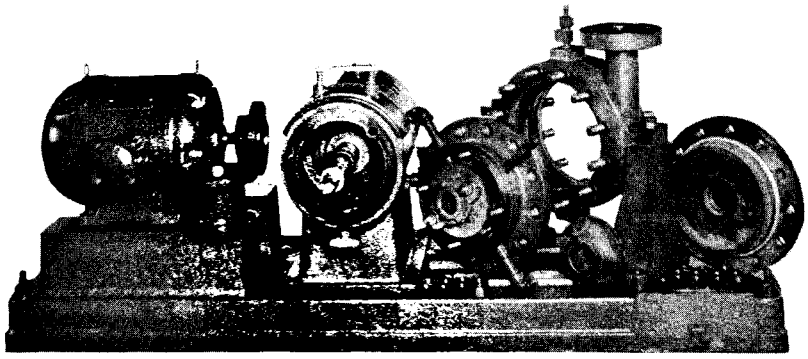
In contrast to cooling-water service, handling abrasive solids of any kind imposes many special problems on a pump. Rubber-lined units with special seals, as shown, are one good answer for ashes, sand, etc. Other designs include packingless types, flat-blade impellers and special arrangements for suction inlet. While the pump is important, so are other system details.

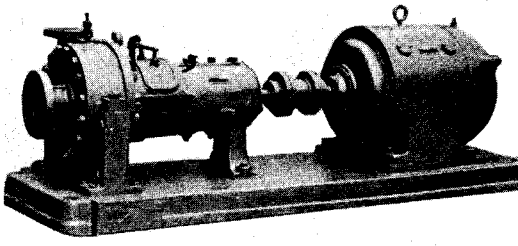


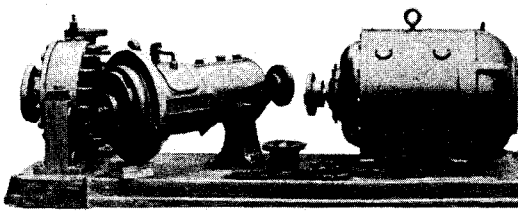


## General purpose

This term applies to all classes of pumps, but centrifugal designs in this category perhaps outnumber all others. Usual meaning of term is a pump to handle clear cool liquids at ambient or moderate temperatures. Often single-stage, these units may be split-case, and are standard-fitted pumps equally good for a number of services. Some handle liquids with solids.

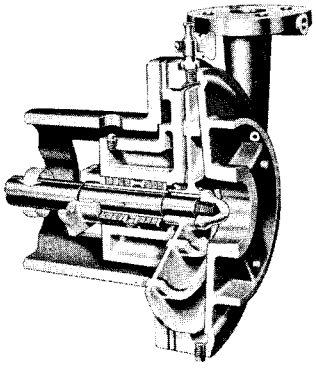


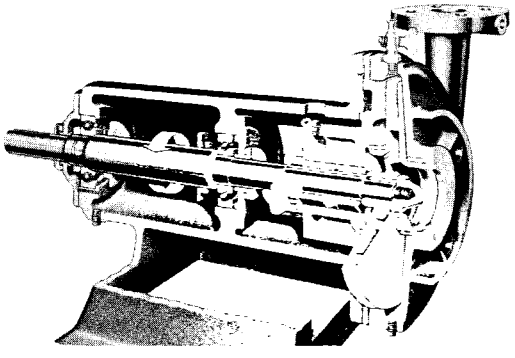


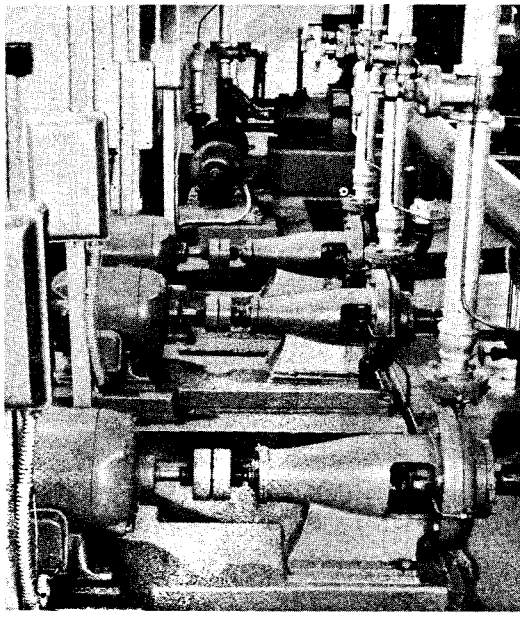


## General process work

In recent years engineers have developed special process-pump designs featuring accessibility, good efficiency and long life. Some designs are available as part of a standard line whereas others are made up to suit the particular service conditions for a specific job. As these illustrations show, ease of maintenance is a prime consideration: complete disassembly is simple.

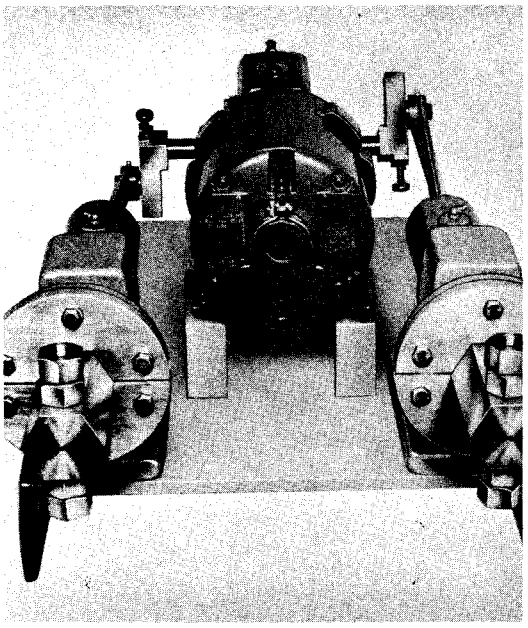


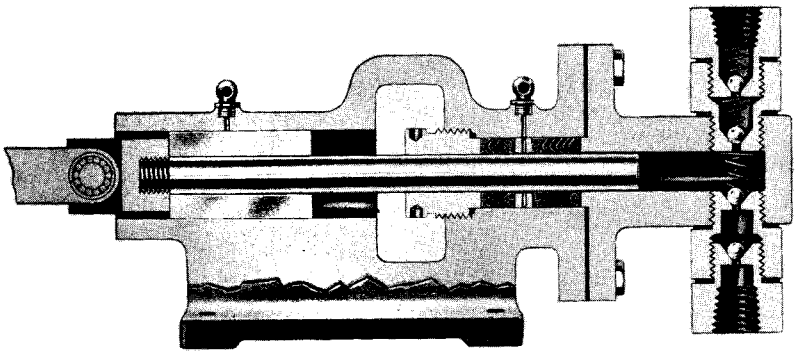




## Chemical process

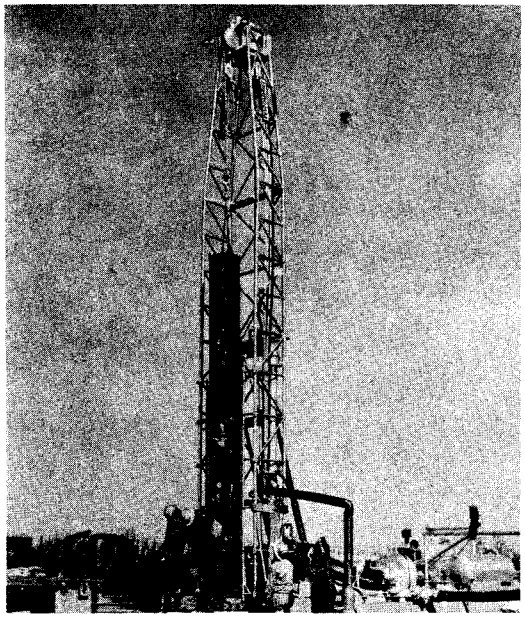
Outwardly resembling the general process pump, units designed for chemical service may differ markedly in materials, stuffing boxes, seals, etc. Usual aim is to produce a single pump line that comes as close as possible to being able to serve all process needs in the chemical industry. Usual units are horizontal, with radially split casings. They can handle a wide range of chemical liquids.

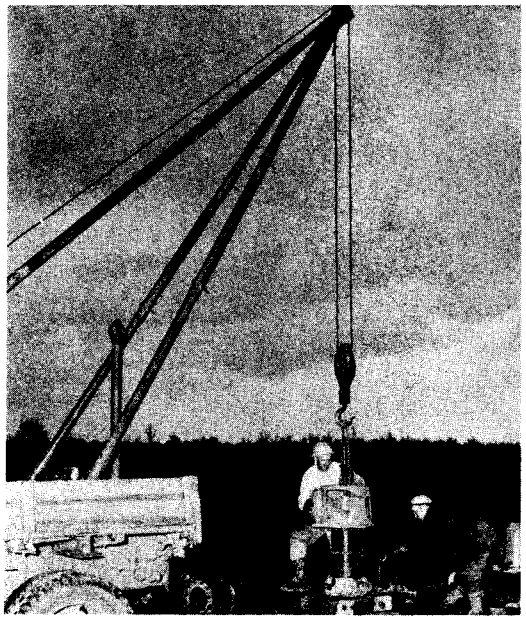


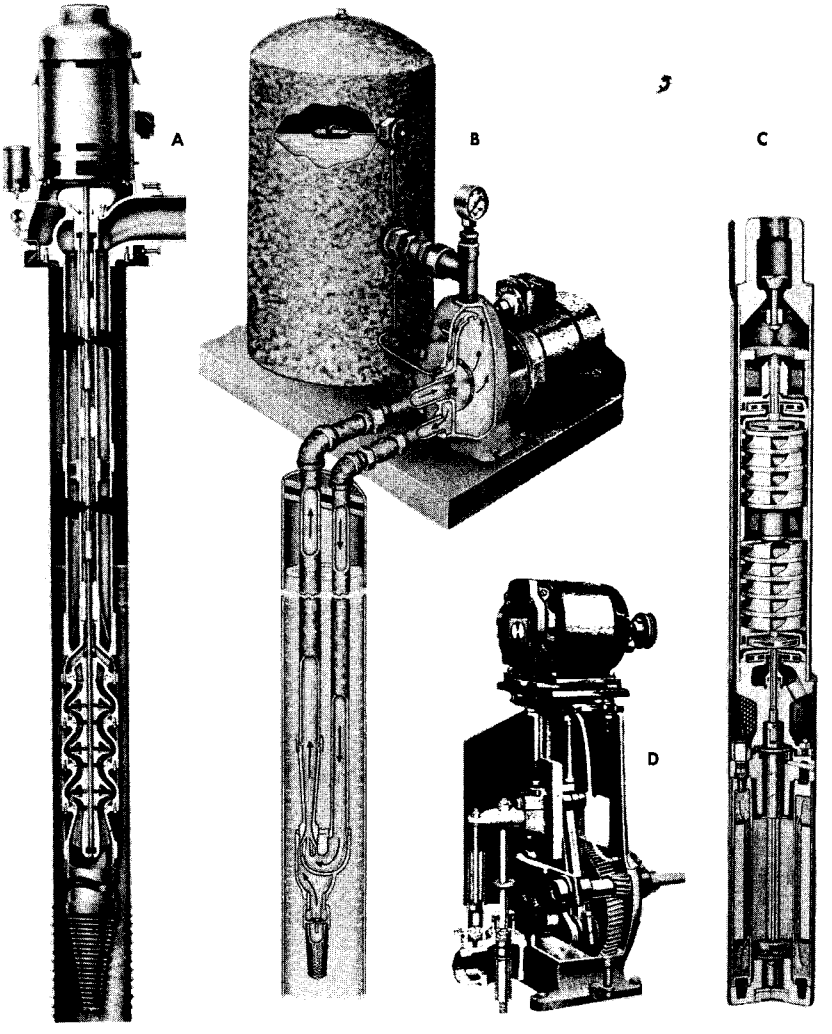


## Chemical feed

Requiring easy adjustment of capacity, chemical-feed pumps are built in a large number of different designs. Unit shown has its reciprocating pumping elements arranged for accessibility. Suction and discharge valves are ball type.

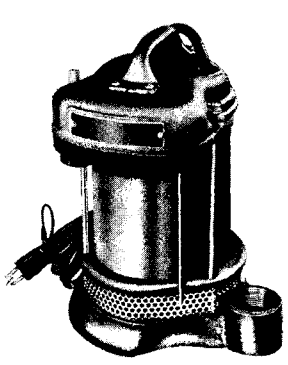


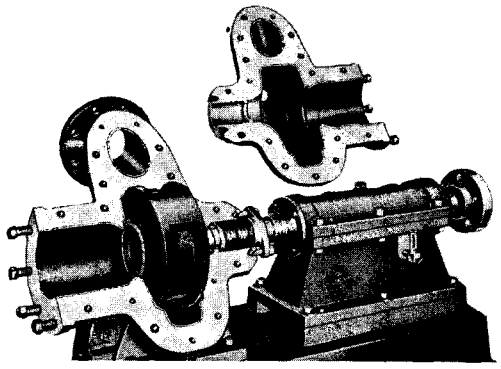


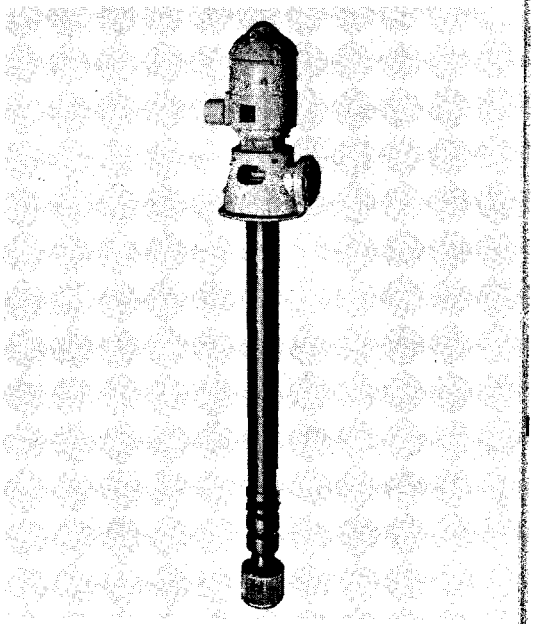



## Well-water supply

Water, like gold, is where you find it. Often this is deep in the earth. So we find many designs for this service. *Deepwell* pump, *A*, often called a *turbine* pump, is a multi-stage diffuser unit. *Jet pumps, B,* bypass a portion of their discharge to an ejector nozzle at the suction screen where it helps improve flow into pump. *Submersible, C,* has motor in well. *D* is *plunger* pump.

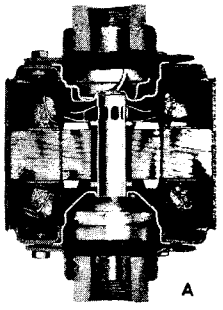




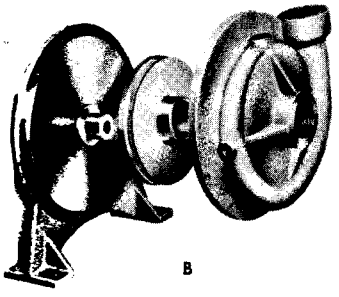


## Sewage and sump

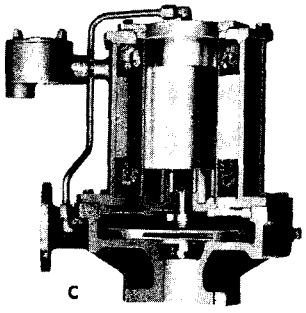
Centrifugal pumps for sewage usually have special non-clogging impellers and a casing that is easily opened for unit inspection, *above right*. Sump pumps, *left* and *extreme right*, may be portable or permanent, depending on needs of the installation. Impeller is almost always the non-clogging type to prevent solids from catching in it. Automatic control is practically universal.



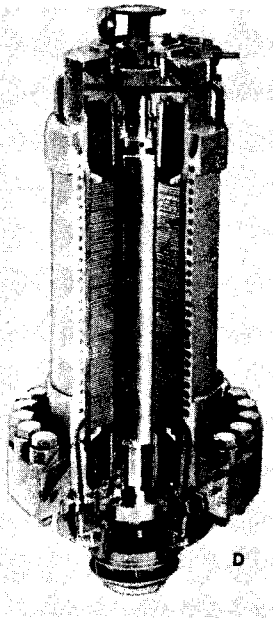
A



B



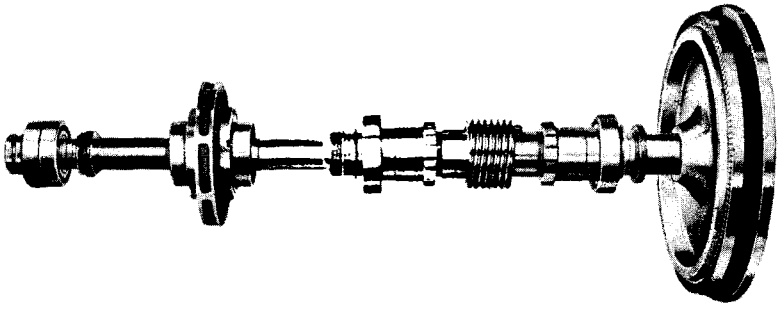
C

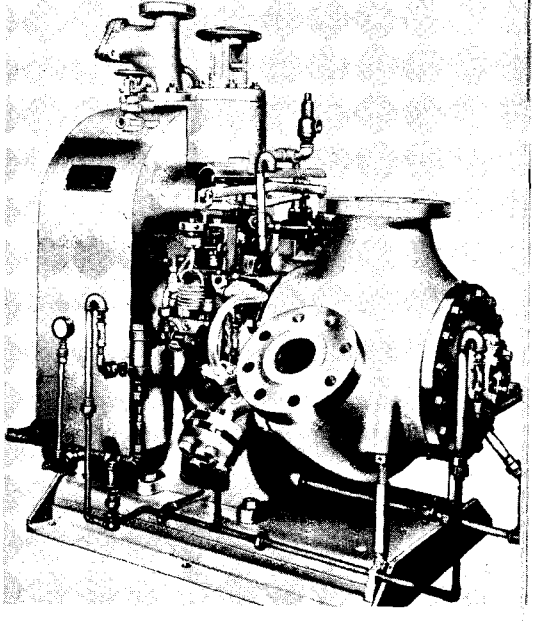


D

## New and special services

Developed in '30s for hot-water circulation, and later refined for chemical and nuclear-power jobs, canned pumps are now strongly bidding for industrial jobs where leak-free service and minimum maintenance are essential. Unit *A* is fractional hp, goes right in pipe. *B* has axial air-gap motor, is built in 10-hp and smaller sizes. *C* is chemical unit, *D* one for nuclear-energy service.

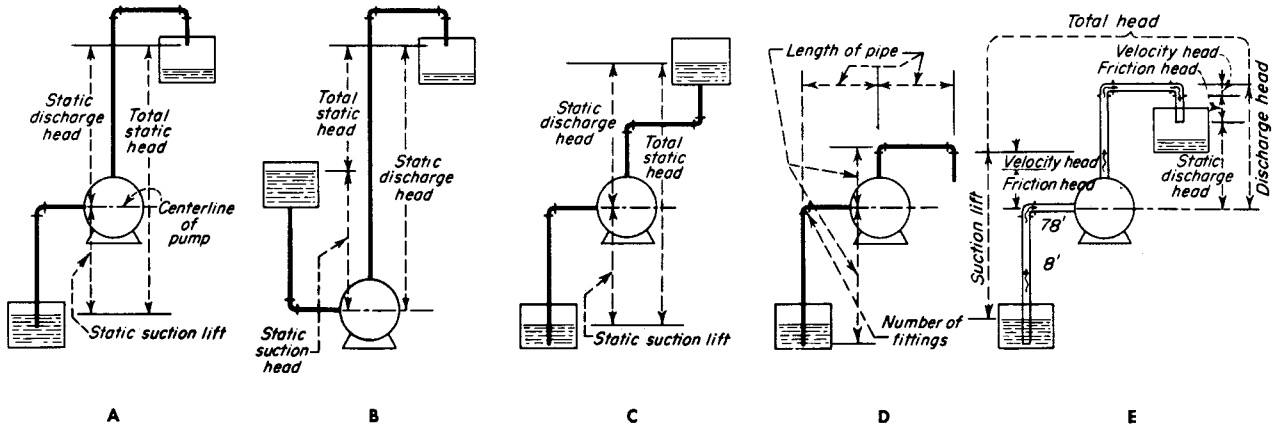




## High-pressure services

Where quick starts, compact installation and steam drive are desirable, as in certain boiler-feed applications, petroleum refining, etc, the high-pressure turbine-driven type shown above has many uses. It consists of a single-stage impeller near one end of the shaft; at the other end is a velocity-staged turbine wheel. Single shaft produces a compact unit easy to install and operate.

## Typical piping hookups for pumps serving industrial loads




# Pump selection . . . 5 steps to

Selecting a pump is much like buying a hat—you have three major decisions to make. These are *size, type* and *best buy*. But of course choosing a pump can be a far more complex problem, especially where unusual or difficult liquid conditions are met. Steps outlined below have proven suitable for typical general-purpose, process and similar applications. Selection of other types — boiler-feed, condensate-return, hydraulic-system, etc. — usually involves analysis of factors not directly related to the pump itself. For example, you might have to compute several plant heat balances before you can make a firm decision on boiler-feed pump type, capacity, drive, etc., best for the existing conditions. Some of these factors were discussed earlier; others are too complex for coverage here.

## 1 Sketch layout (see diagrams above)

Trying to pick a pump without a sketch of the system layout is like a miner trying to work without his lamp. You're in the dark from start to finish. Base sketch on actual job, as planned. Show all piping, fittings, valves, equipment, etc. Mark length of pipe runs of sketch. Be sure to include all vertical lifts. Where piping is complex, an isometric sketch is often extremely helpful.

## 2 Determine capacity (see Table I)

Job conditions fix capacity required. For example, maximum steam flow from the exhaust of a turbine, along with steam conditions, determines the minimum amount of cooling water at a given temperature. Seasonal changes, safety factor desired, etc., influence actual capacity chosen. Where demand is unknown and must be estimated, Table I is a big help in indicating typical ranges to be expected. It does *not,* however, give exact values because there can be wide variations from one installation to another. Except for small pumps and those for metering and proportioning, capacity is expressed in gallons per minute (gpm).

## 3 Figure total head (see Tables II, III)

Diagrams above show various heads in typical pumping systems. Definitions, *facing page,* will help you understand the meanings of various terms. If a pump handles 500 gpm of water through 86 ft of 6-in. suction pipe, diagram above right, and there is one medium-radius elbow having a resistance equal to 14 ft of straight pipe, total equivalent length of suction pipe is 86 + 14 = 100 ft. Friction loss from Table II is 1.7 ft of water per 100 ft of pipe. Velocity head is almost 0.5 ft and static suction lift is 8 ft. Hence, suction lift is 8 + 1.7 + 0.5 = 10.2 ft. Discharge head is found in a similar way, using discharge pipe size, length of runs and fittings in the line. Total head is the sum of suction lift and discharge head. Where we have a static suction head, as in the second hookup from the left, we subtract suction head from discharge head to obtain the total head. Always have pump manufacturer check your head calculations. Then you'll be certain the pump is suitable.

## 4 Study liquid conditions

Up to this point we've determined but two requirements our pump must meet — head and capacity. Now we come to characteristics of the liquid and their effect on pump selection. Liquid heavier than water (specific gravity greater than 1) takes more horsepower to be moved from one point to another; lighter liquids require less power. Liquid temperature and vapor pressure fix the net positive suction head needed for satisfactory operation. Unless you are thoroughly experienced with this phase of pump selection, it is best to have the manufacturer check suction conditions. Viscosity of liquid affects horsepower, head and

## DEFINITIONS

STATIC SUCTION LIFT is vertical distance, ft, from supply level to pump centerline; pump above supply.

STATIC SUCTION HEAD: same as static suction lift, but pump is below supply level.

STATIC DISCHARGE HEAD is vertical distance, ft, from pump centerline to point of free delivery.

TOTAL STATIC HEAD is vertical distance, ft, from supply level to discharge level.

FRICTION HEAD is pressure, in ft of liquid, needed to overcome resistance of pipe, fittings.

SUCTION LIFT is static suction head plus suction friction head and velocity head.

SUCTION HEAD is static suction head minus suction friction head and velocity head.

DISCHARGE HEAD is static discharge head plus discharge friction head and velocity head.

TOTAL HEAD is sum of suction lift and discharge head. Where there is suction head, total head is difference between discharge and suction heads.

NOTE: Some engineers use *dynamic suction lift, dynamic discharge head* and *total dynamic head* instead of terms above. While the word *dynamic* helps express idea of motion, ie, head when liquid is flowing, the simpler terms are favored.

## I: TYPICAL WATER REQUIREMENTS

| Usual buildings* | | | Cities and towns | |
|---|---|---|---|---|
| Fixture | Cold, gpm | Hot, gpm | Population | Total**, gpm |
| Water-closet flush valve | 45 | 0 | 1000 | 800 |
| Water-closet flush tank | 10 | 0 | 2000 | 1200 |
| Urinals, flush valve | 30 | 0 | 3000 | 1500 |
| Urinals, flush tank | 10 | 0 | 4000 | 1700 |
| Lavatories | 3 | 3 | 5000 | 2000 |
| Shower, 4-in. head | 3 | 3 | 6000 | 2200 |
| Shower, 6-in. and larger | 6 | 6 | 8000 | 2700 |
| Needle bath | 30 | 30 | 9000 | 2900 |
| Shampoo spray | 1 | 1 | 10,000 | 3100 |
| Baths, tub | 5 | 5 | 20,000 | 5100 |
| Kitchen sink | 4 | 4 | 40,000 | 8700 |
| Pantry sink, ordinary | 2 | 2 | 50,000 | 11,000 |
| Pantry sink, large bibb | 6 | 6 | 60,000 | 13,000 |
| Slop sinks | 6 | 6 | 100,000 | 19,000 |
| Wash trays | 3 | 3 | 150,000 | 28,000 |
| Laundry tray | 6 | 6 | 180,000 | 33,000 |
| Garden-hose bibb | 10 | 0 | 200,000 | 37,000 |

*Approximate maximum flow from fixtures: to obtain maximum *probable* flow, multiply maximum possible flow by a usage factor based on previous experience.

**Total includes water for domestic supply and fire protection. Where city or town is predominantly industrial, a greater flow will probably be required.

# better results

capacity, as well as class of pump chosen. Here, again, your best bet is the manufacturer. Liquid pH influences pump materials, p 85, while solids affect mechanical construction.

## 5 Choose class and type

Studying the layout, like trying on a hat, tells us what *size* (capacity and head) pump we need. This furnishes our first lead as to what class of pump is suitable. For example, where high-head small-capacity service is required, table p 77, shows that a reciprocating pump would probably be suitable. Reviewing the liquid characteristics furnishes another clue to class because exceptionally severe conditions may rule out one or another right at the start. Sound economics dictates choosing the pump that provides the lowest cost per gallon pumped over the useful life of the unit.

Operating factors deserving recognition when deciding on class include type of service (continuous or intermittent), running-speed preferences (high-speed pumps often cost less), future load expected and its effect on pump head, possibility of parallel or series hookup, and many others peculiar to a given job. These factors deserve as much study as head and capacity: they're just as important.

Once you know class and type you're ready to check these in a rating table, p 104, or a rating chart as on p 87. As you can see, the table lists pump capacity, head, horsepower, etc. Where required capacity and head, or both, falls between two tabulated values, it is usual practice to choose a pump to meet the next larger condition where this is not too far from the existing job conditions. Otherwise, another make or type of pump may have to be used.

One important fact to keep in mind is that many large pumps are custom-built for a given plant or application. Under these conditions the pump manufacturer performs most of the steps listed above, basing his design on information supplied by the engineer on the job.

## II: PIPE FRICTION LOSS FOR WATER

(Wrought-iron or steel Schedule 40 pipe in good condition)

| Dia, in. | Flow, gpm | Velocity, ft per sec | Velocity head, ft of water | Friction loss, ft of water per 100 ft pipe |
|---|---|---|---|---|
| 2 | 50 | 4.78 | 0.355 | 4.67 |
| 2 | 100 | 9.56 | 1.42 | 17.4 |
| 2 | 150 | 14.3 | 3.20 | 38.0 |
| 2 | 200 | 19.1 | 5.68 | 66.3 |
| 2 | 300 | 28.7 | 12.8 | 146 |
| 4 | 200 | 5.04 | 0.395 | 2.27 |
| 4 | 300 | 7.56 | 0.888 | 4.89 |
| 4 | 500 | 12.6 | 2.47 | 13.0 |
| 4 | 1000 | 25.2 | 9.87 | 50.2 |
| 4 | 2000 | 50.4 | 39.5 | 196 |
| 6 | 200 | 2.22 | 0.0767 | 0.299 |
| 6 | 500 | 5.55 | 0.479 | 1.66 |
| 6 | 1000 | 11.1 | 1.92 | 6.17 |
| 6 | 2000 | 22.2 | 7.67 | 23.8 |
| 6 | 4000 | 44.4 | 30.7 | 93.1 |
| 8 | 500 | 3.21 | 0.160 | 0.424 |
| 8 | 1000 | 6.41 | 0.639 | 1.56 |
| 8 | 2000 | 12.8 | 2.56 | 5.86 |
| 8 | 4000 | 25.7 | 10.2 | 22.6 |
| 8 | 8000 | 51.3 | 40.9 | 88.6 |
| 10 | 1000 | 3.93 | 0.240 | 0.497 |
| 10 | 3000 | 11.8 | 2.16 | 4.00 |
| 10 | 5000 | 19.6 | 5.99 | 10.8 |
| 10 | 7500 | 29.5 | 13.5 | 24.0 |
| 10 | 10,000 | 39.3 | 24.0 | 42.2 |
| 12 | 2000 | 5.73 | 0.511 | 0.776 |
| 12 | 5000 | 14.3 | 3.19 | 4.47 |
| 12 | 10,000 | 28.7 | 12.8 | 17.4 |
| 12 | 15,000 | 43.0 | 28.7 | 38.4 |
| 12 | 20,000 | 57.3 | 51.1 | 68.1 |

## III: RESISTANCE OF FITTINGS AND VALVES

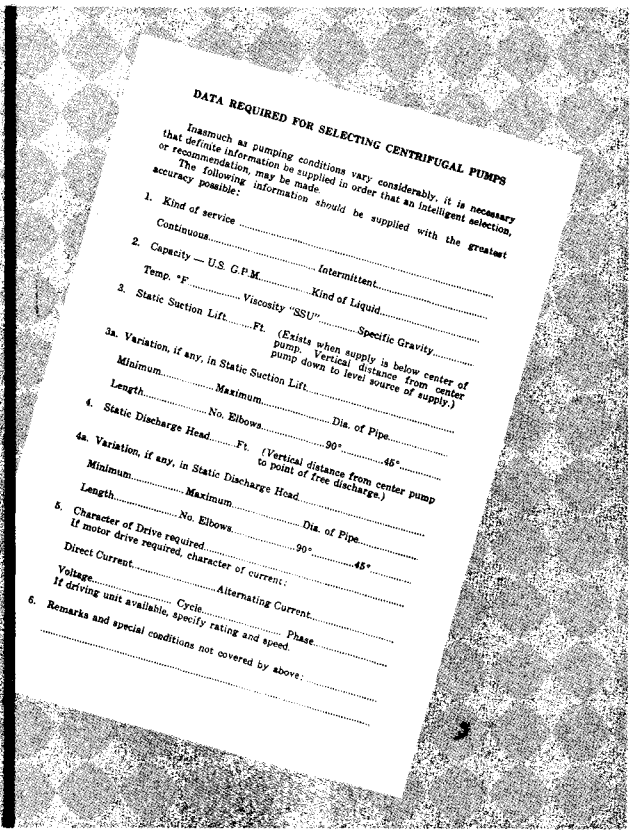
(Length of straight pipe, ft, giving equivalent resistance)

| Pipe size, in. | Std ell | Med-rad ell | Long-rad ell | 45-deg ell | Tee | Gate valve, open | Globe valve, open | Swing check, open |
|---|---|---|---|---|---|---|---|---|
| 1 | 2.7 | 2.3 | 1.7 | 1.3 | 5.8 | 0.6 | 27 | 6.7 |
| 2 | 5.5 | 4.6 | 3.5 | 2.5 | 11.0 | 1.2 | 57 | 13 |
| 3 | 8.1 | 6.8 | 5.1 | 3.8 | 17.0 | 1.7 | 85 | 20 |
| 4 | 11.0 | 9.1 | 7.0 | 5.0 | 22 | 2.3 | 110 | 27 |
| 5 | 14.0 | 12.0 | 8.9 | 6.1 | 27 | 2.9 | 140 | 33 |
| 6 | 16.0 | 14.0 | 11.0 | 7.7 | 33 | 3.5 | 160 | 40 |
| 8 | 21 | 18.0 | 14.0 | 10.0 | 43 | 4.5 | 220 | 53 |
| 10 | 26 | 22 | 17.0 | 13.0 | 56 | 5.7 | 290 | 67 |
| 12 | 32 | 26 | 20.0 | 15.0 | 66 | 6.7 | 340 | 80 |
| 14 | 36 | 31 | 23 | 17.0 | 76 | 8.0 | 390 | 93 |
| 16 | 42 | 35 | 27 | 19.0 | 87 | 9.0 | 430 | 107 |
| 18 | 46 | 40 | 30 | 21 | 100 | 10.2 | 500 | 120 |
| 20 | 52 | 43 | 34 | 23 | 110 | 12.0 | 560 | 134 |
| 24 | 63 | 53 | 40 | 28 | 140 | 14.0 | 680 | 160 |
| 36 | 94 | 79 | 60 | 43 | 200 | 20.0 | 1000 | 240 |

## Typical centrifugal-pump rating table

| Size | Gpm | Total head, ft 10 | 15 | 20 | 25 | 30 |
|---|---|---|---|---|---|---|
| 2C | 100 | | | 1000-.8 | 1060-1.0 | 1150-1.2 |
| | 150 | | | 1070-1.2 | 1150-1.5 | 1240-1.7 |
| | 200 | | | | 1290-2.1 | 1360-2.4 |
| 3CS | 150 | 750-.53 | 850-.78 | 950-1 | 1030-1.2 | 1100-1.5 |
| | 200 | | 950-1.1 | 1010-1.4 | 1100-1.7 | 1170-2 |
| | 250 | | | 1170-1.9 | 1190-2.3 | 1260-2.6 |
| | 300 | | | | | 1400-3.5 |
| 3CL | 200 | 690-.63 | 800-.95 | 910-1.3 | 1010-1.6 | 1110-2.05 |
| | 300 | 870-1.2 | 950-1.6 | 1000-1.9 | 1100-2.4 | 1170-2.8 |
| | 400 | | | 1200-3.1 | 1230-3.7 | 1290-4.1 |
| | 500 | | | | | 1490-5.8 |
| 4C | 400 | 750-1.3 | 850-1.8 | 940-2.4 | 1040-3 | 1120-3.7 |
| | 600 | | | 1080-4 | 1170-4.6 | 1210-5.5 |
| | 800 | | | | | 1400-8.4 |
| 1¼D | 25 | | 617-.21 | 707-.03 | 778-.40 | 845-.51 |
| | 50 | | 680-.37 | 760-.49 | 865-.63 | 900-.76 |
| | 75 | | | 856-.78 | 916-.94 | 980-1.1 |
| | 100 | | | | | |
| | 125 | | | | | |
| | 150 | | | | | |
| 2DL | 150 | | 820-.93 | 850-1.1 | 930-1.35 | 990-1.6 |
| | 200 | | | 970-1.8 | 1040-2.1 | 1080-2.3 |
| | 250 | | | | | |
| | 300 | | | | | |

*Example: 1080-4 indicates pump speed is 1080 rpm; actual input required to operate pump is 4 hp.*



DATA REQUIRED FOR SELECTING CENTRIFUGAL PUMPS

Inasmuch as pumping conditions vary considerably, it is necessary that definite information be supplied in order that an intelligent selection, or recommendation, may be made. The following information should be supplied with the greatest accuracy possible:

1. Kind of service .....
Continuous..... Intermittent.....
2. Capacity — U.S. G.P.M..... Kind of Liquid.....
Temp. °F..... Viscosity "SSU"..... Specific Gravity.....
3. Static Suction Lift..... Ft. (Exists when supply is below center of pump. Vertical distance from center pump down to level source of supply.)
3a. Variation, if any, in Static Suction Lift.....
Minimum..... Maximum.....
Length..... No. Elbows..... Dia. of Pipe.....
4. Static Discharge Head..... Ft. (Vertical distance from center pump to point of free discharge.)
4a. Variation, if any, in Static Discharge Head.....
Minimum..... Maximum.....
Length..... No. Elbows..... Dia. of Pipe.....
5. Character of Drive required..... 90°..... 45°.....
If motor drive required, character of current:
Direct Current..... Alternating Current.....
Voltage..... Cycle..... Phase.....
If driving unit available, specify rating and speed.....
6. Remarks and special conditions not covered by above:
.....

# Other considerations in choosing pumps

Our previous two pages outline usual steps in choosing a pump for typical industrial services. There are cases, however, where selection is better made by the pump builder.

**Estimating data sheets,** *above right,* are available from manufacturers to aid you in making a complete statement of conditions a new pump must meet. When sending such an estimate to a manufacturer it is wise to include a clear free-hand sketch of the installation.

While the sheet shown is for a centrifugal pump, forms for reciprocating and rotary estimates resemble this closely. Having the manufacturer select your pump insures getting the right unit, *provided* you supply the information he needs.

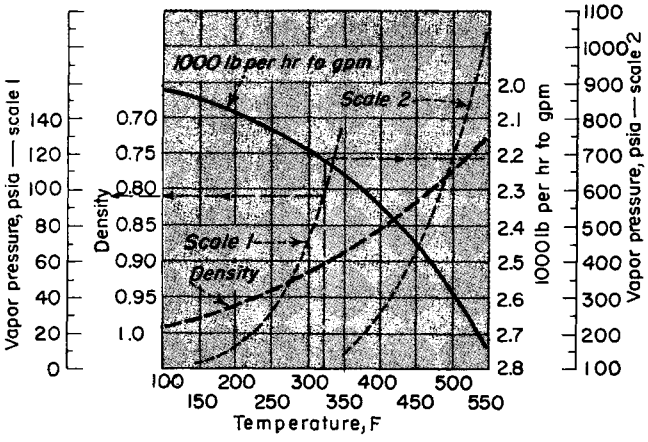
**Net positive suction head** is often listed on estimate sheets and must be entered to give a complete picture of pumping conditions. This term gives pressure available or required to force a given flow, gpm, into the impeller, cylinder or casing of a pump. For uniformity, npsh is stated as feet of liquid equivalent to required pressure in psi over and above vapor pressure of liquid at pumping temperature.

Every pump has its individual required npsh characteristics which the manufacturer can plot on a performance curve. Npsh at any point on the curve is head in feet of liquid pumped equivalent to pressure in psi required to force liquid into the pump. Values shown by pump manufacturer are based on tests and are regularly corrected to the centerline of the pump.

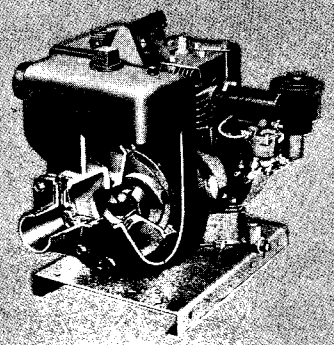
As engineer in charge of plant services you must locate the pump and design the suction piping so available npsh is equal to or greater than npsh required by pump. Curves, *right,* give vapor pressure of water at different temperatures. They also give conversion factors for changing flow from lb per hour to gpm. Both are useful in planning.

**Pipe sizes** for lines where flow demand is likely to change or resistance may increase over a period of years require careful study. If sized only on basis of today's demands or resistance, we may find that what was once an economical installation becomes a money-waster.

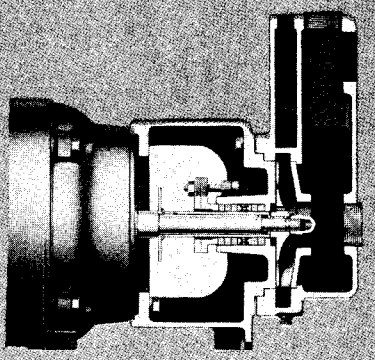
**Complete Analysis.** Though not all jobs warrant it, a piping system can be completely analyzed for present and future operations by using pump characteristic and system-head curves like those on p 86. But instead of plotting one system-head curve, a series, one for each operating condition, is plotted. Study of these will show just what we may expect from a given pump today, tomorrow, and five or more years from now. This is a job for the engineer in the plant and it deserves more attention than it usually receives.



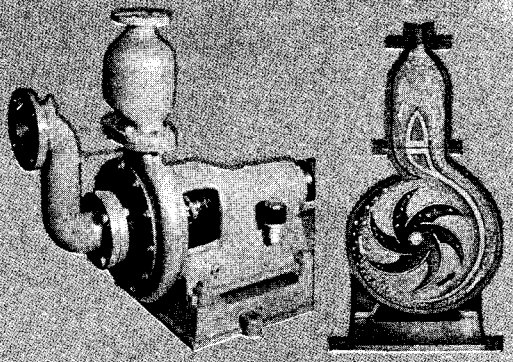
## SIX SELF-PRIMING PUMPS



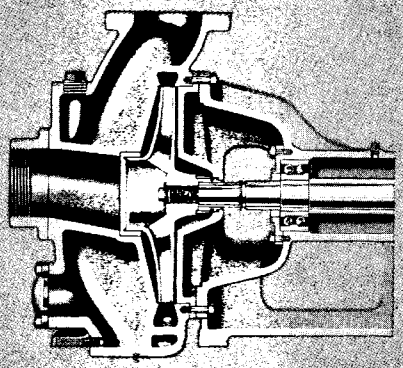
DIFFUSER priming method here does not return liquid to suction side of the pump



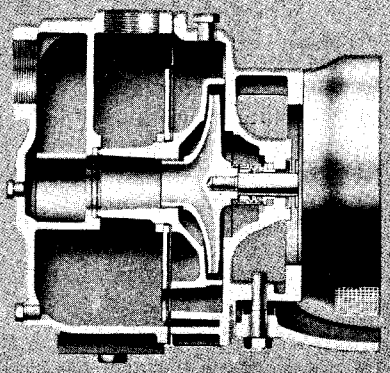
DOUBLE VOLUTE recirculates liquid-vapor mixture during prime, separates vapor



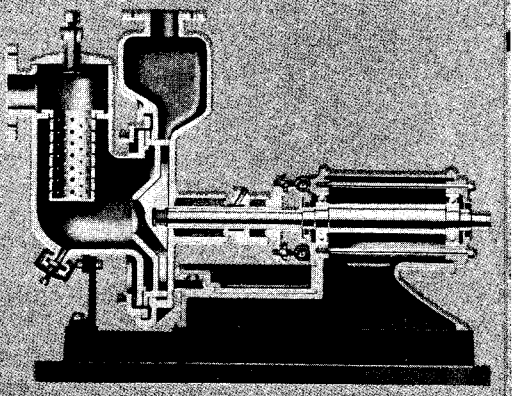
AIR SEPARATOR and two discharge ports in pump give priming action in this unit



PRIMING CHAMBER in this unit surrounds straight-in suction; no valves are used

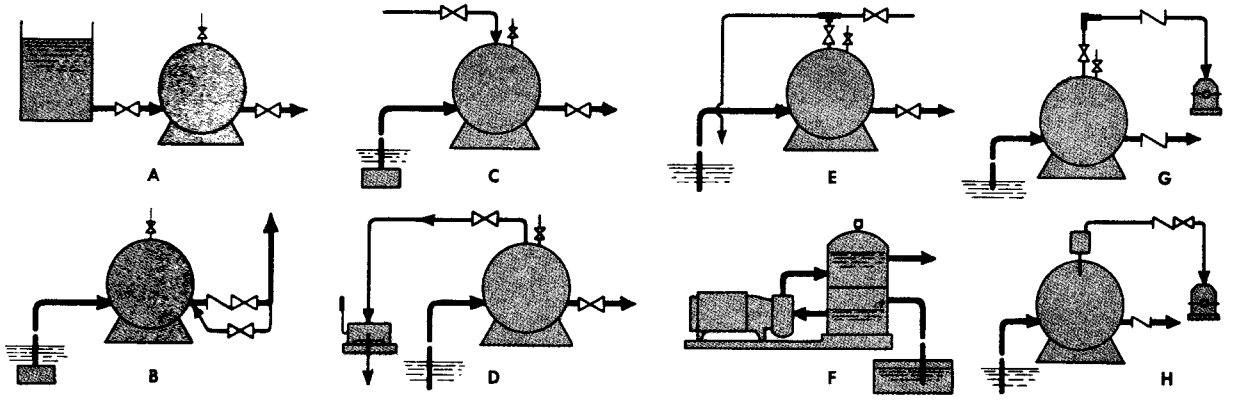


LIQUID flows into lower volute and out upper volute during priming in this unit



SLOTS in impeller vanes permit air to be entrained by priming liquid in this pump

## EIGHT AUXILIARY PRIMING METHODS




# Priming pumps

Positive-displacement pumps — reciprocating and rotary — are self-priming for total suction lifts to about 28 ft. when in good condition. But with long suction lines, high lifts or other abnormal conditions, they must be primed.

Centrifugal pumps are not self-priming; on a suction lift they must be primed. Either special self-priming units may be used or auxiliary priming equipment may be installed.

Illustrations at top of this page show six modern self-priming units. Designs vary from one maker to another, but a liquid reservoir of some type on the discharge is common. It holds priming liquid and serves as an air separator. Other designs have a liquid reservoir on both suction and discharge, liquid being circulated from discharge to suction on prime. Automatic valves or hydraulic action stop circulation after pump primes. Some pumps circulate liquid continuously.

Auxiliary equipment for pump priming includes ejectors, vacuum pumps, etc., used in hookups like those sketched.

With a flooded suction, *A*, open casing air-vent petcocks and then slowly open suction gate valve. Incoming liquid pushes air from casing. Bypass around discharge check valve, *B*, permits using liquid in discharge line. Foot valve, *C*, holds water in suction line, is augmented by auxiliary supply. Separate pump, *D*, draws air from casing for priming. Or an ejector, *E*, does same job. Priming tank, *F*, holds supply of liquid large enough to establish flow through pump on starting. Vacuum pumps, *G* and *H*, are manually and automatically controlled to prime the main pump.

# Pumps on the job

## Installation

Your best bet on correct installation procedures is the instruction manual supplied with your pump by its manufacturer. Remember, he spends considerable time, money and skill in assembling these manuals with the hope you will use them when the pump reaches your plant. Use the manual even where a contractor is responsible for installing the pump. Don't assume grouting, alignment and bolting-down are so simple that they needn't be checked.

Today's pumps, as a class of machinery, are among the most carefully built units available. So you are starting with a good product that will give years of dependable service without a hitch. Use *Standards of Hydraulic Institute* for many general helpful hints on pump location, layout and run of suction piping, type of fittings, etc. In many instances these will duplicate the manufacturer's manual but it is well worthwhile to become familiar with the *Standards* because they contain much other valuable information. Past articles in POWER will also help you strengthen your background on pump installation. See the following issues for sure-fire aids: Feb 1945, Nov 1948, Jan 1950, June 1952, Feb, April 1953.

## Operation

Major items of concern in pump operation include satisfactory prime (p 105), right direction of rotation, correct adjustment of packing, if used, a good supply of the recommended lubricant, adjustment of sealing-liquid flow, and proper opening of valves in suction and discharge lines. Generally speaking, correctly installed pumps run without troubles for years if checked regularly.

Once again, your surest and shortest road to good operation is your instruction manual because it is aimed specifically at your pump and, for custom-built units, at your particular installation. There is no reliable substitute for the years of experience pump manufacturers have had with jobs similar to or exactly like yours. So use your manual carefully and see that your operators know the whys and wherefores of the units under their care. Correct starting, running and stopping procedures help spin off troublefree years of dependable service. Of course, you must be alert at all times for conditions inside and outside the pump that may affect operation. See the following POWER articles for good tips: April, July and Sept 1950, Jan, April, May and June 1952, June and Nov 1953.

## Maintenance

Checks with manufacturers and pump operators show a growing tendency to bypass the annual tear-down for inspection of interior parts. Opinion on this subject is divided, however, and you'll have to evaluate the various arguments in terms of your job and pumping conditions before reaching a final decision on annual tear-down. As an example of what is possible, some boiler-feed pumps have been on the line for over 100,000 hours without being opened for inspection or overhaul. And these units are still ticking off the hours, day after day.

Manual supplied by manufacturer should be your maintenance bible because it contains numerous tips on problems that may arise. It is especially important for large units where disassembly and assembly may be major undertakings requiring a high degree of mechanical skill and experience. Of course, you should make full use of advice the manufacturer can offer on specific maintenance problems. And you are certain to gain by making periodic checks of pump performance to see if it departs markedly from the guarantee. See the following POWER articles: Jan, April, May and June 1952, June and Nov 1953.

POWER wishes to thank pump manufacturers and engineers throughout the country not only for supplying illustrations but for much helpful advice and criticism in the preparation of this handbook.

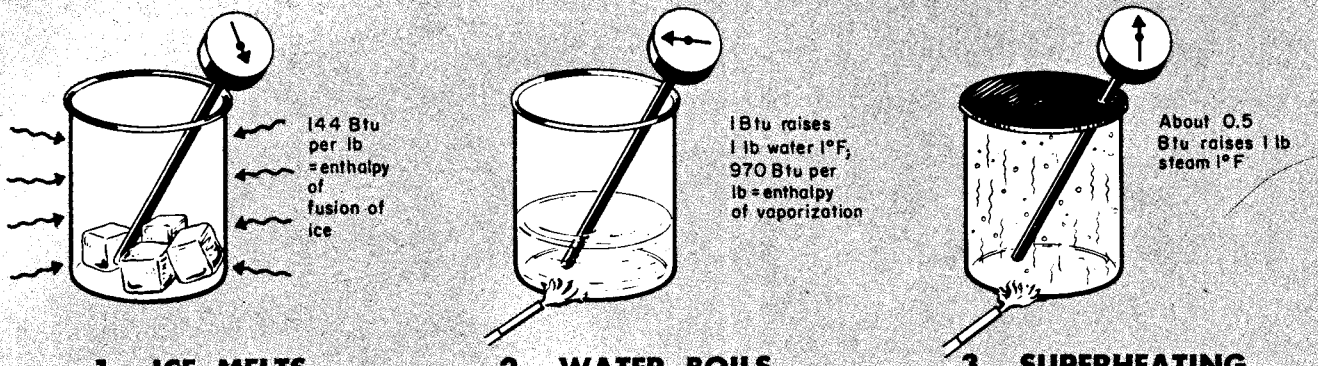
# Refrigeration

A half century has seen the refrigeration industry grow from a relatively few ponderous slow-speed machines for making ice to literally millions of units, large and small, serving about every activity known to man. Air conditioning, just one well-known application of refrigeration, continues to boom with the end nowhere in sight. Add to this a growing number of industrial applications ranging from straight food processing and storage to a wide variety of precision manufacturing, and you get some indication of refrigeration's importance as a power service today.

This report points out that modern units are more compact, turn at higher speeds, have greater capacity per pound of equipment, are more reliable and easier to operate than machines of yesterday. You'll get the boiled-down facts on systems and their components—compressors, evaporators, condensers, controls, piping, brines and refrigerants. Also, power men will benefit from this report's timely pointers highlighting current practices in equipment selection and operation, plus the helpful tips in applying the various refrigerants available today for best results.

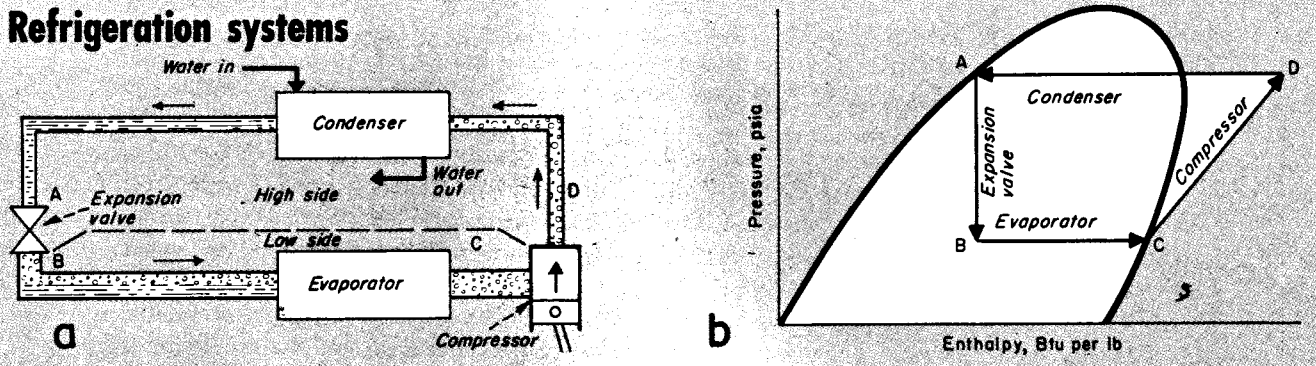
a **Power** special report

## Heat transfer


144 Btu per lb = enthalpy of fusion of ice
1 Btu raises 1 lb water 1°F; 970 Btu per lb = enthalpy of vaporization
About 0.5 Btu raises 1 lb steam 1°F

1 ICE MELTS 2 WATER BOILS 3 SUPERHEATING

## Refrigeration systems




7 VAPOR-COMPRESSION REFRIGERATION

# How machines make cold

Making cold depends on a few simple principles. Of these the most important is that heat always flows from a warmer to a cooler body—never the reverse. So to cool a warm object we place it near a cold one like a block of ice, or in a cold well, pond or lake. Using natural ice and cold water to remove heat provided man's first cooling systems.

**Heat flow.** Put some ice cubes in a jar with a thermometer, Fig. 1, and heat flowing from the room and surrounding air melts the cubes if the room temperature is above 32 F. To melt 1 lb of ice, 144 Btu must be absorbed. During melting, temperature of ice and water formed stays at 32 F. Conceivably, we could cool an entire room with ice cubes, but the process would not be efficient.

If a concentrated heat source is applied to a jar, Fig. 2, water formed from the ice cubes boils when it reaches a temperature of 212 F. Once again, heat is flowing from a warm body to a cooler one.

To make the water change to steam, a gaslike vapor, we must add about 970 Btu per lb of water. This heat quantity is the *enthalpy of vaporization.* During the period when water is changing to steam, there is no temperature change. Heat absorbed by ice in melting is *enthalpy of fusion.*

When all the water changes to steam at 212 F, further addition of heat causes superheating, meaning that the temperature of the steam is higher than that corresponding to its pressure, Fig. 3.

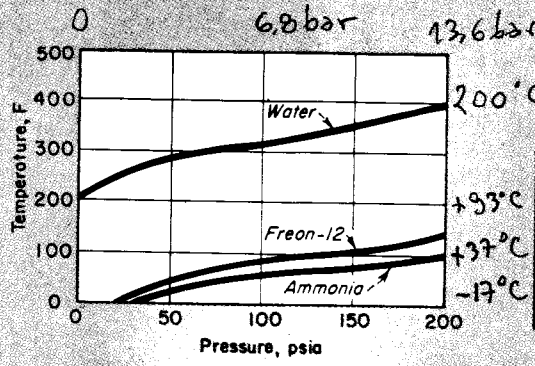
**Vaporization, condensation.** Water boils at 212 F when subjected to atmospheric pressure. Increasing the pressure on surface of a liquid raises the temperature at which it boils. Curves, Fig. 4, show some boiling temperatures.

Condensation, the reverse of vaporization, also occurs at constant temperature. For a given pressure of the liquid, condensaton occurs at the same temperature as vaporization. Thus, for water at atmospheric pressure (14.7 psia) vaporization or boiling occurs at 212 F, as does condensation. Reducing the pressure to 1 in. Hg absolute gives boiling and condensation temperatures of 79 F.

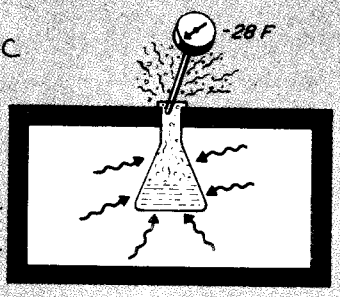
**Refrigerants** are fluids that, with few exceptions, boil at low temperatures at atmospheric pressure. For example, ammonia at 14.7 psia boils at −28 F, while F-12 (Freon-12) boils at about −21 F, at the same pressure. Boiling and condensation processes of refrigerants are the same as for water.

Using these concepts, let's arrange an insulated box as in Fig. 5, with a flask of ammonia suspended in it. With normal atmospheric pressure on the ammonia surface, the liquid boils at −28 F, absorbing about 602 Btu per lb of liquid vaporized. Since little heat can pass through the insulated sides of the box, heat needed for vaporization will come from the air or other contents of the box. Thus we have a crude system for producing refrigeration.

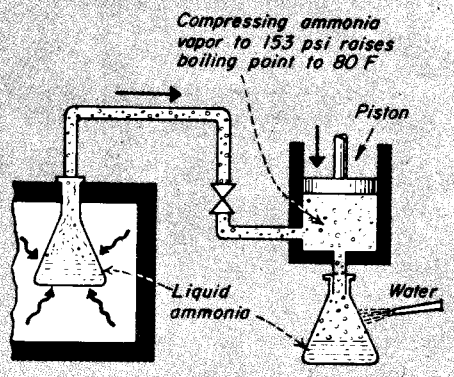
System in Fig. 5 might find use were refrigerants cheap, readily obtained from nature and noninjurious to human beings. But most refrigerants are not, and even if they were,



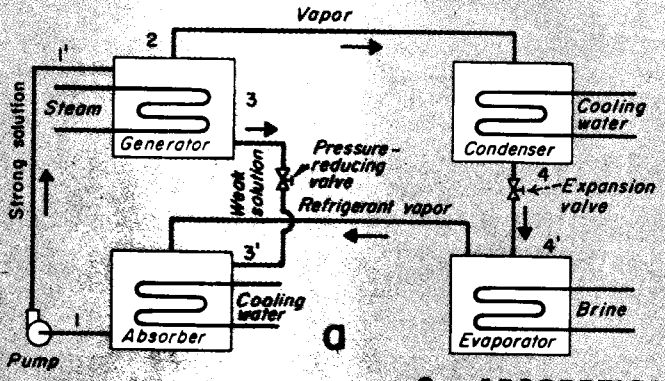

4 PRESSURE AND BOILING

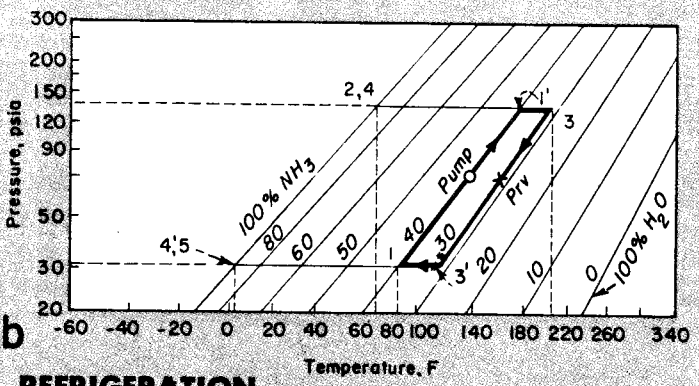



5 BOILING AMMONIA




6 RECOVERING AMMONIA




8 ABSORPTION REFRIGERATION

the hookup, Fig. 5, is impractical. So to make our system practical, we must find some way of recovering the ammonia vapor after it has absorbed heat.

We could arrange to suck it into another chamber, but to condense it we'd need, as we recall from Fig. 2 and 3, a cooling medium at a temperature less than −28 F because condensation occurs at the same temperature as boiling.

Since condensation temperature depends on vapor pressure, if we compress ammonia to a high enough pressure we can condense it by cooling with air or water at ordinary atmospheric temperatures (40 to 70 F). Fig. 6 shows how this can be done, using water for cooling.

**Compression system.** Fig. 6 can be further refined to that shown in Fig. 7a, where an expansion valve controls refrigerant flow from *high* to *low* side. Fig. 7b shows a pressure-enthalpy (Ph) diagram for the system in Fig. 7. Starting at the expansion-valve inlet *A*, refrigerant in the liquid state flows through the valve, a portion of it changing to a vapor. From *B* to *C* the liquid is vaporized in the evaporator (corresponding to the flask). Compression is from *C* to *D*, desuperheating and condensation from *D* to *A*.

**Compression systems** may use reciprocating, centrifugal, gear or rotary compressors and any one or more of a variety of refrigerants, depending on the job.

**Steam-jet units** are also the compression type. They use water as their refrigerant, have steam jets to lower the pressure, reducing the boiling point of the water.

**Absorption system.** Here, heat is used to raise pressure of the refrigerant, instead of a compressor. Fig. 8a shows the components of a typical system. Absorption refrigeration relies on ability of some liquids and solids to absorb vapors when cold, give them up when hot.

## DEFINITIONS

**REFRIGERATING EFFECT** is the amount of heat absorbed in the evaporator, which equals that removed from space cooled. It is measured by subtracting the enthalpy (heat content) of one pound of refrigerant entering expansion valve from the enthalpy of the same pound leaving evaporator

**TON OF REFRIGERATION** is about equivalent to melting one ton of ice in 24 hr, or 288,000 Btu per 24 hr; 12,000 Btu per hr; 200 Btu per min

**REFRIGERANT HANDLED** in pounds per ton-minute is found by dividing 200 Btu per min by the refrigerating effect, Btu per lb of refrigerant

**WORK OF COMPRESSION** is amount of heat added to refrigerant in compressor. Measured by subtracting enthalpy of one pound of refrigerant at suction from enthalpy of same pound at the compressor discharge

**COEFFICIENT OF PERFORMANCE** is the ratio of refrigerating effect to work of compression. A high coefficient of performance means high efficiency of the refrigeration cycle

**HORSEPOWER PER TON** is mechanical input in horsepower, divided by tons of refrigerating effect produced by unit

**STANDARD-TON CONDITIONS** specify the pressures a machine must operate at to have certain evaporator and condenser temperatures—for example, 5 and 86 F, respectively. Tonnage produced at these temperatures is standard rating of the machine. Other temperatures are also used

A common combination is ammonia as refrigerant, and water as *absorbent* or *solvent*. In Fig. 8a, refrigerant gas from evaporator is absorbed by water in the absorber. Heat, applied in the generator, drives off ammonia at condenser pressure. Fig. 8b is a simple cycle diagram for the system.

# Refrigeration machines

Shown on these two pages are a few of the many different designs for refrigeration machines of various types. There is far wider variation in the designs of machines for compression systems—reciprocating, rotary, gear and centrifugal — than for absorption and steam-jet systems.

**Reciprocating compressors** of modern design, Fig. 1-6, are characterized by smaller size, lighter weight, higher speeds and greater reliability than their forebears of the 1900s. Early units were steam driven at slow speeds (about 50 rpm) and used liquid refrigerant or oil for cooling.

Today most reciprocating compressors are motor driven at speeds up to 3600 rpm. Water or air cools the cylinders, making the entire unit simpler and more rugged. Improvements in production methods have lowered unit cost, enabling more industries to use greater amounts of refrigeration in their operations. Complete or semiautomatic control of compressor operation reduces the amount of attendance.

**Hermetically sealed** reciprocating and rotary compressors have the compressing element and drive motor sealed in a single housing. Relatively new, they are finding increasing use in a wide variety of applications. Advantages include elimination of the shaft seal of the open-type unit, easier lubrication and less operating noise. Some designs are cooled by refrigerant gas entering compressor.

**Centrifugal refrigeration compressors,** introduced commercially about 30 years ago, are characterized by large capacity, suitability for extremely low temperatures and ability to carry varying loads with satisfactory efficiency at all loads within their operating range.

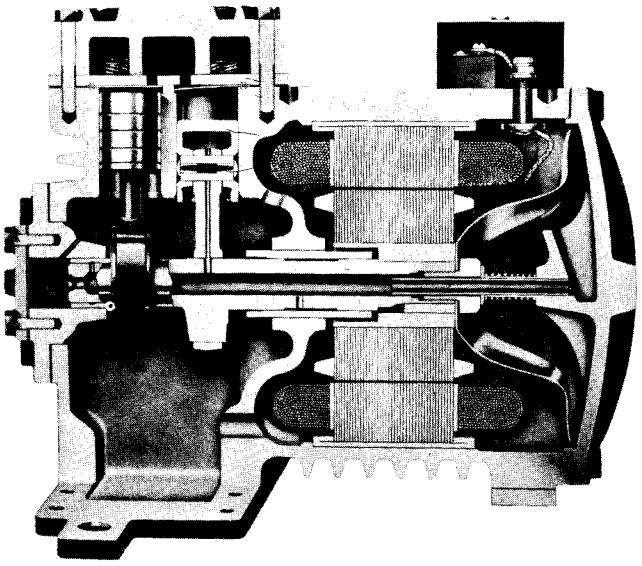
Essentially high-speed units, centrifugal compressors may be directly driven by steam turbines. Motor or internal-combustion-engine drive is also used. Top speed of these compressors today is about 8000 rpm. While many standard model centrifugal compressors are available, it is not uncommon to design and build some units for a specific job, selecting one of a large number of suitable refrigerants.

**Absorption machines,** making a comeback after many years' neglect, are catching on fast for air-conditioning and process jobs. With steam as their source of heat, they can provide a summer load leading to advantageous steam rates. Other advantages include quiet operation, light weight, easy control.

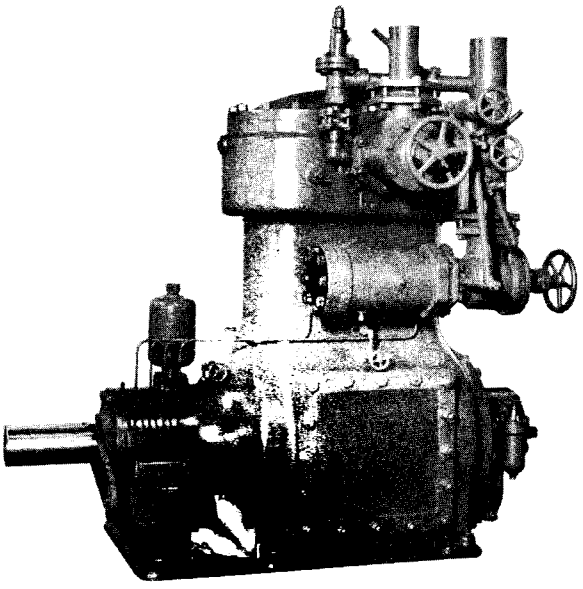
**Steam-jet units,** using only steam and water, are simple, safe and low-cost, supply chilled water at 35 F, or above.

## OTHER METHODS

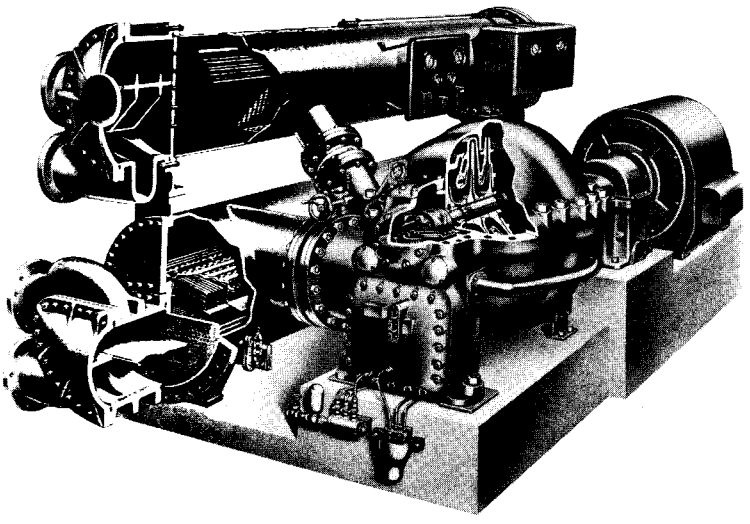
Today, practically all of industry's cooling is produced by one or more machines of the types shown on these two pages. But some aircraft have air-cycle units for cabin cooling. Magnetic cooling, using paramagnetic salts, produces low temperatures by adiabatic demagnetization of the salt. Electronic cooling, based on the Peltier effect, consists of a series of junctions made of copper and zinc alloys. These surround a container. Electric current produces cooling at one junction. At present, both these methods are still in the laboratory stage.



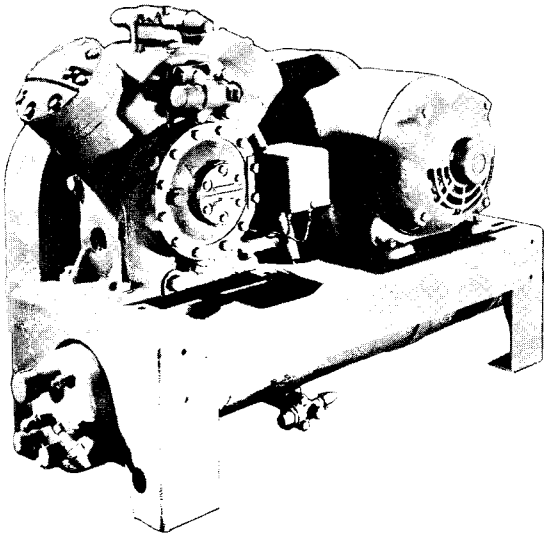
**1** Single-acting hermetically sealed Freon compressor can be maintained in field, has capacities to 110,000 Btu per hr



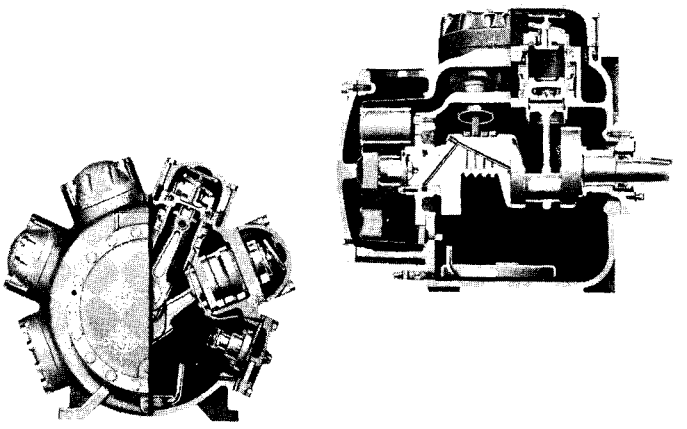
**4** Twin-cylinder ammonia compressor for 5 to 100 tons is a typical unit for this refrigerant; belt or direct drive



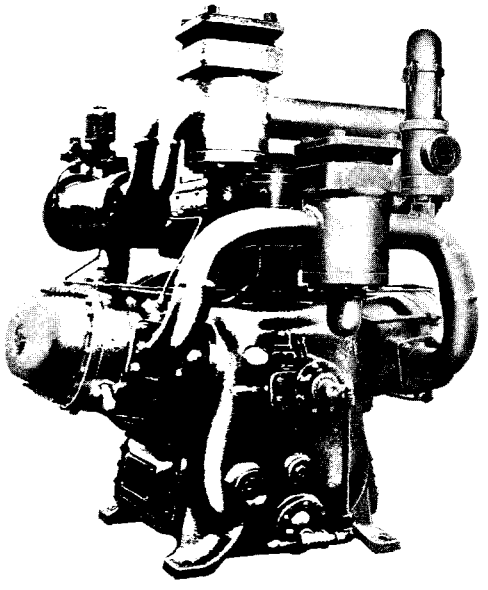
**7** Centrifugal refrigerating machines of this design chill brines to —150 F, are built in capacities to 3000 tons



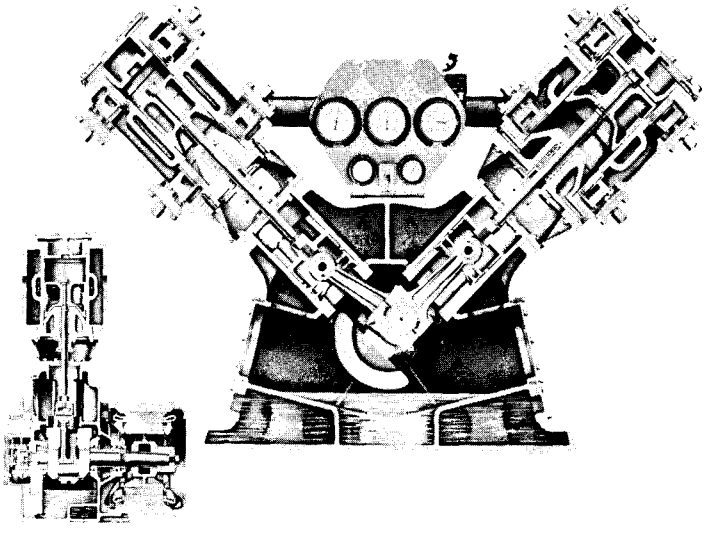
**2** Built with two or three cylinders, Freon-12 units like this one are designed for loads of 3, 5, 7.5 and 10 tons



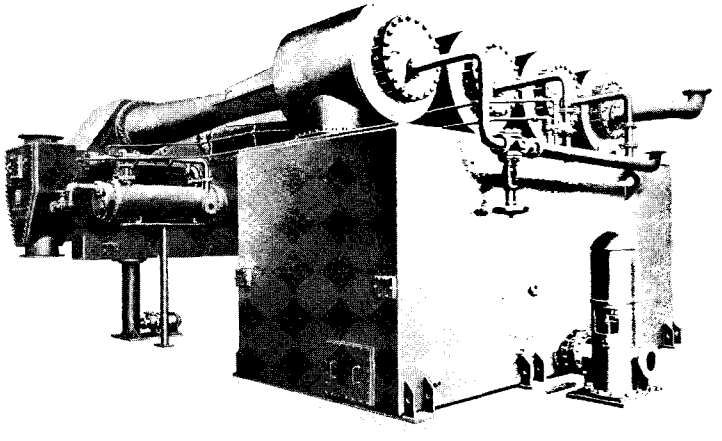
**3** Built with 4, 6 or 8 cylinders in V, W or VV arrangement, single units have 10- to 50-ton capacity on Freon 12, 22



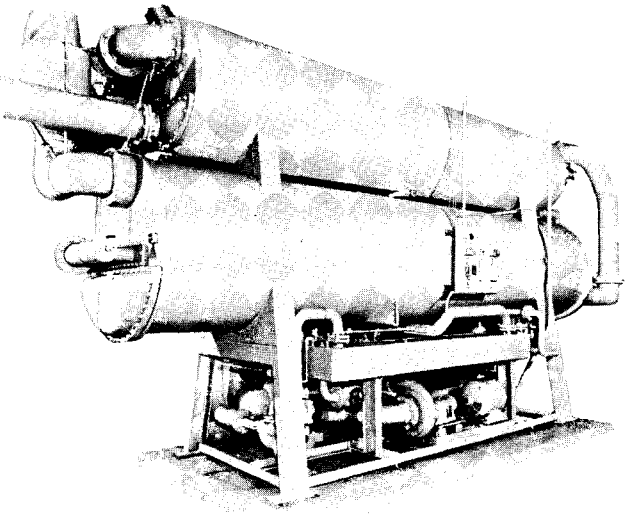
**5** Booster compressor handles large gas volumes at low pressure in low-temperature systems, acting as the first stage



**6** Y-type ammonia compressor is built as a single- or two-stage double-acting unit with integral motor on the shaft



**8** Steam-jet refrigeration unit uses water for its refrigerant, delivers 35-F or higher temperature chilled water



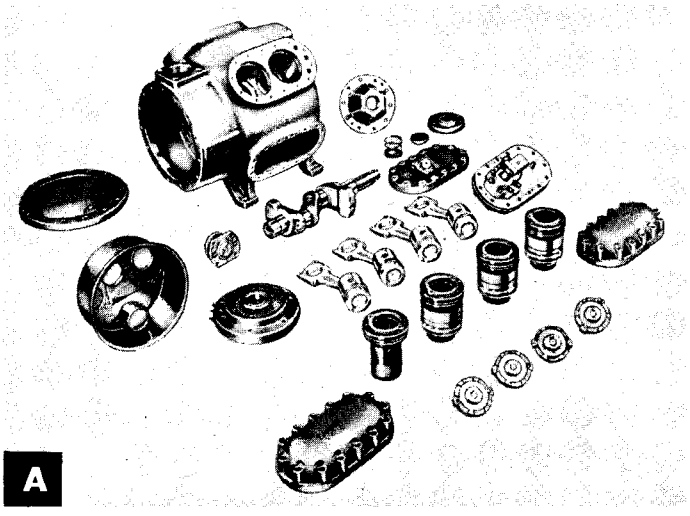
**9** Absorption refrigerating machine uses steam or hot liquid with lithium-bromide absorbent: compact, vibration-free

# Refrigeration-machine components

## Reciprocating

Higher speeds for today's reciprocating compressors give greater displacement, produce more capacity from a given bore and stroke. Freon compressor, disassembled at **A**, runs at 1750 rpm, uses lightweight reciprocating parts. Unit takes 0.99 hp per ton at 40-F-suction, 105-F-condenser temperature. Multistep capacity control is actuated by suction pressure; external pneumatic or electrical triggering may also be used.

Ammonia compressor components **B** through **F** are usually of heavier construction than for Freon. Connecting rods **B** are often die-forged steel with precision-bearings. Plate-type discharge valves **C** operate on a pressure differential. Poppet and strip-type valves are also used. Suction valves **F** are in compressor head, along with the discharge valves, or in piston top. A typical piston for a high-speed ammonia compressor is shown at **D**; crankshaft at **E**.

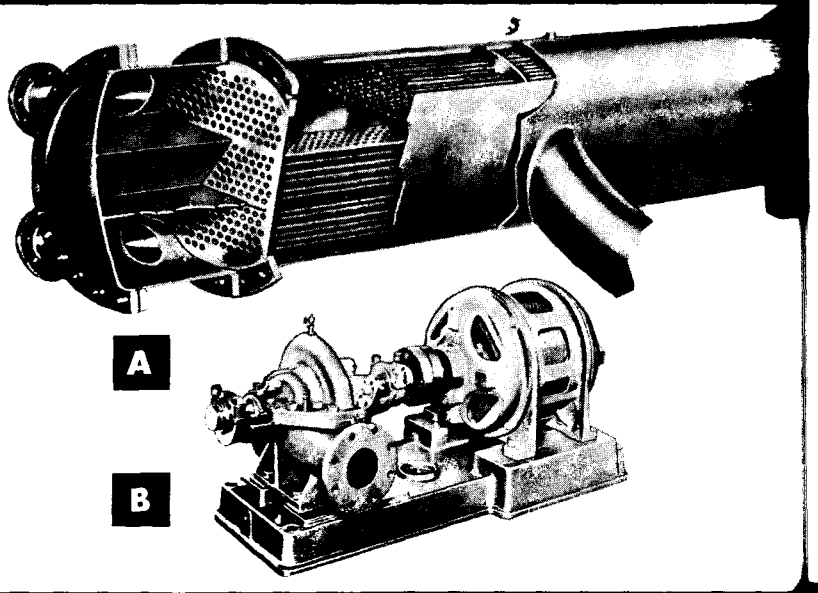



## Centrifugal

Centrifugal compressors raise refrigerant pressure in steps through each stage, usually are built as complete units with compressor, condenser, cooler, drive and auxiliaries on a single base, making a compact, high-capacity package.

Divided-waterbox multiple-pass shell-and-tube condensers **A** are used. Refrigeration machines of this type almost invariably chill water or brine, which is circulated to the points where cooling is required. One or more centrifugal pumps **B** circulate the water or brine to be chilled through the shell-and-tube cooler **C**.

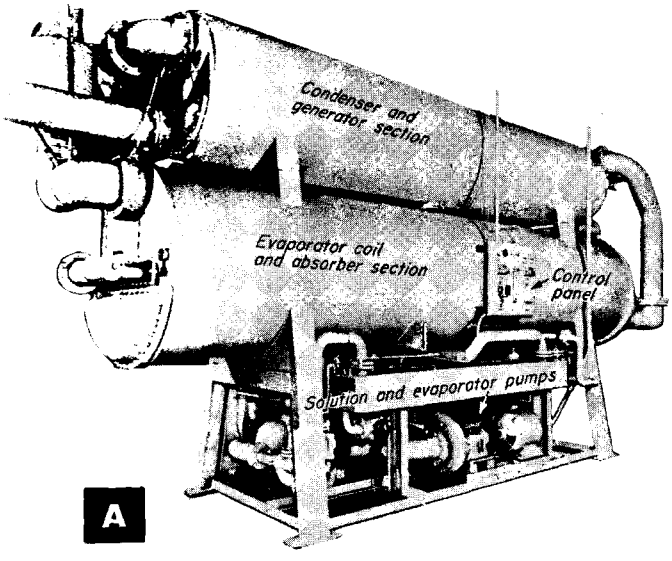
To reduce power input to compressor, an interstage flash chamber **D** may be used between the condenser and cooler. In this chamber a portion of the refrigerant flashes into vapor, subcooling the liquid refrigerant. Most centrifugal machines also have a noncondensable-gas purge system.

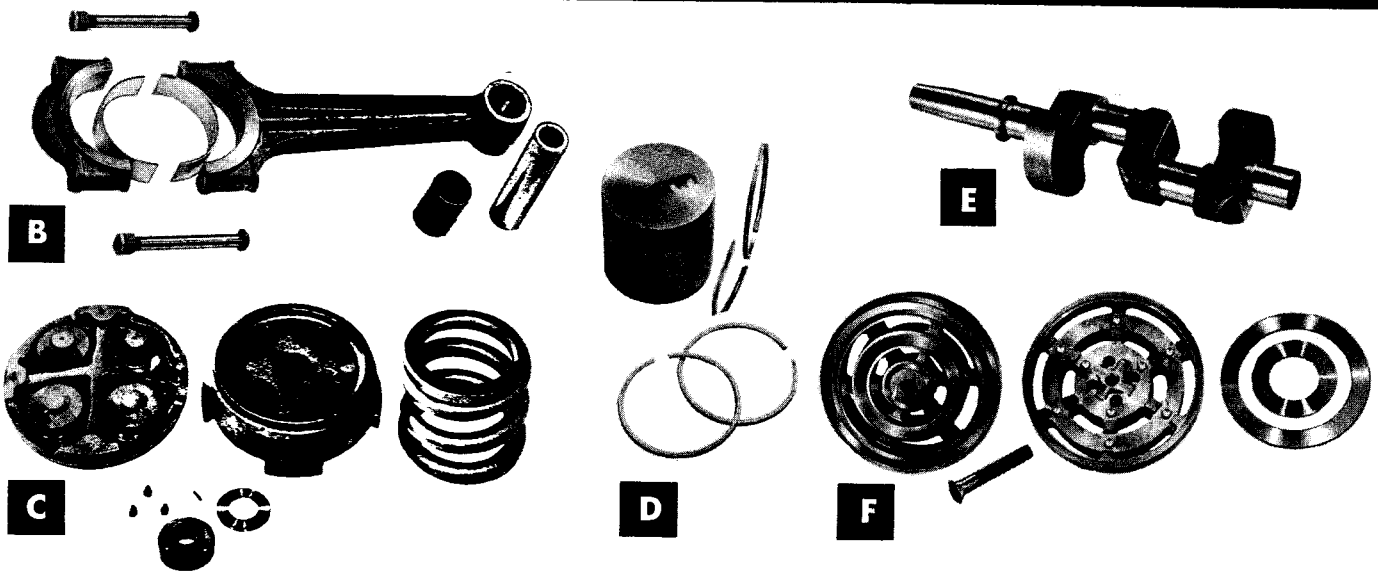


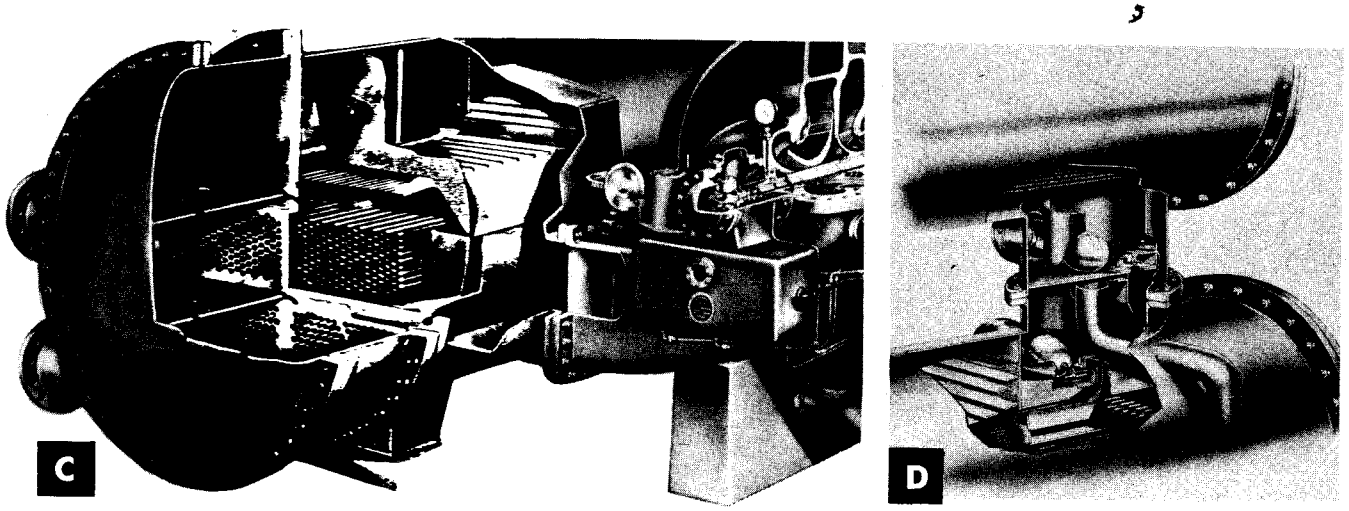

## Absorption and steam-jet

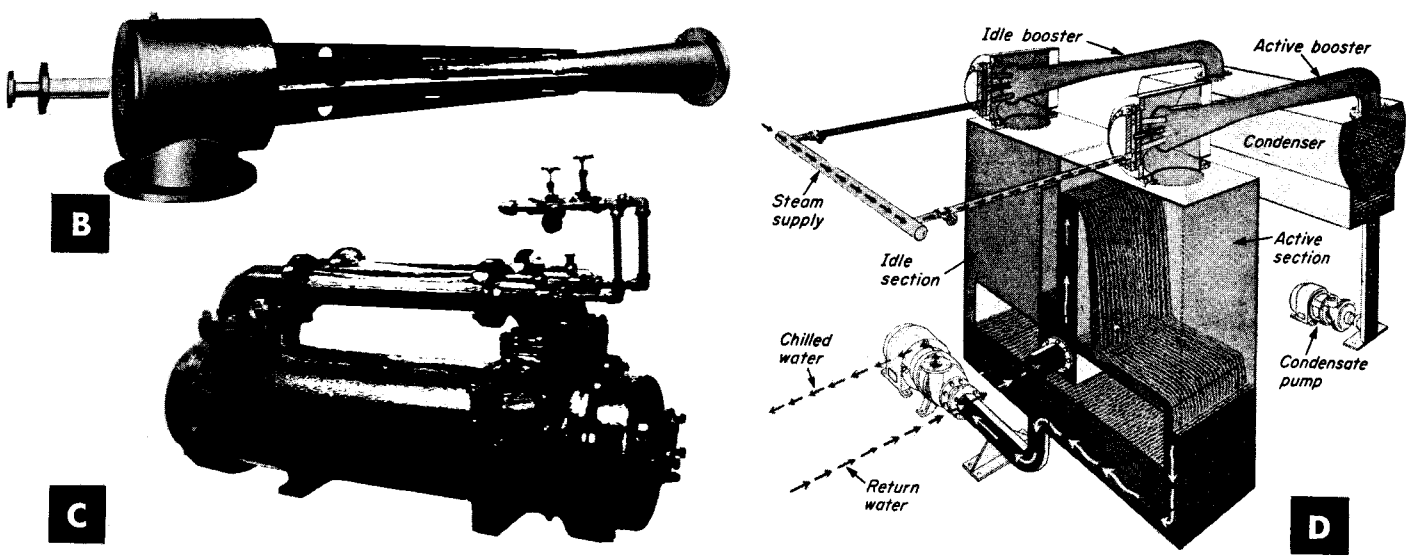
Modern absorption units are a far cry from the early collection of tanks, pipes and coils of yesteryear. Typical of today's designs, the machine at **A** has its condenser and generator in a single vessel, evaporator and absorber in another vessel. Both are supported by the same set of legs with solution and evaporator pumps slung beneath.

Heart of a steam-jet refrigeration unit is the booster **B**. It has several steam nozzles discharging steam at 3500 to 4250 fps across a suction chamber and into a venturi-shaped compression tube **D**. Water vapor from evaporator enters booster suction where it is entrained by the jets and discharged to the diffuser; here compression takes place. Condenser vacuum is maintained by a 2-stage steam-jet ejector **C**. For special installations, where high-pressure steam is not available, vacuum pumps are used.




B
C
D
E
F

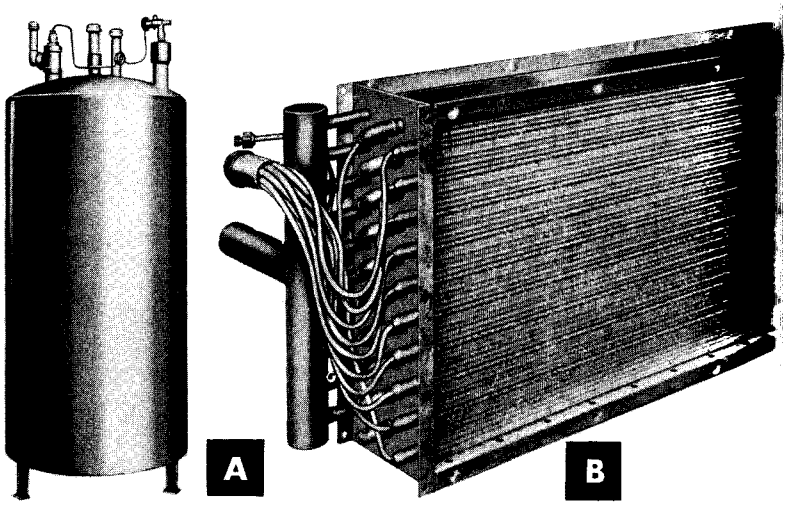

C
D


B
C
Idle booster
Active booster
Condenser
Steam supply
Idle section
Active section
Chilled water
Condensate pump
Return water
D

# System components

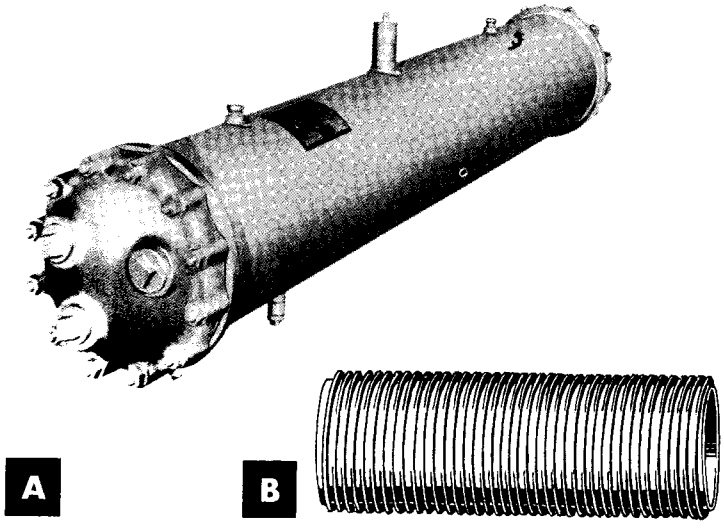
## Evaporators

Many different types of evaporators are used, depending on the job. Watercooling type **A** supplies cooled water for indirect air-conditioning systems, is built for Freon in a wide range of capacities. Direct-expansion cooling coil **B** is fed just enough refrigerant by the expansion valve so all liquid is converted to gas before the refrigerant reaches suction connection of the evaporator. This type is widely adopted for air-conditioning ducts. Cascade-type chiller **E** is a double-pipe unit fitted with a spring-type bladed scraper **C** to keep pipe clean. Liquid to be cooled circulates through the inner pipes, refrigerant between inner and outer pipes. Motor rotates scrapers. Shell-and-tube dry- or direct-expansion liquid chiller using Freon is shown at **D**. Vertical-header-type coil **F** for can-ice plants, may have float control or thermal-valve feed. Plate-type evaporators **G** have continuous loops of steel tubing between evacuated plates.




## Condensers

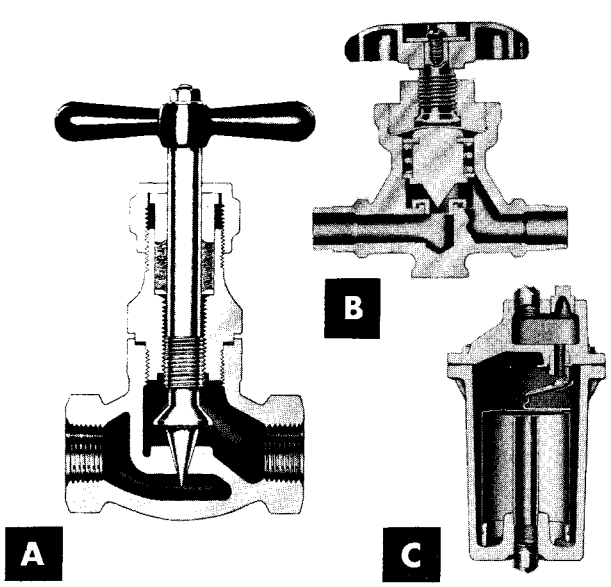
Shell-and-tube Freon condenser, the most widely used type for this refrigerant in larger-capacity systems, is shown at **A**. It has finned tubes **B** to increase the heat-transfer area and efficiency. There may be either two or four water passes, depending on job. Older ammonia systems often had double-pipe condensers but these are gradually being replaced by shell-and-tube units similar to **A**, either horizontal or vertical construction. The condenser-tower unit **C** is designed to meet the need for water conservation in industry. It consists of a multipass straight-tube condenser, a receiver, oil trap, water pump and cooling tower. Air-cooled condensers **D** are used for small units, up to about 3 hp. Larger capacities almost always have watercooling, sometimes in newer double-pipe units. Evaporative condensers **E** receive their cooling effect from both air and water, are widely used in small and large sizes.

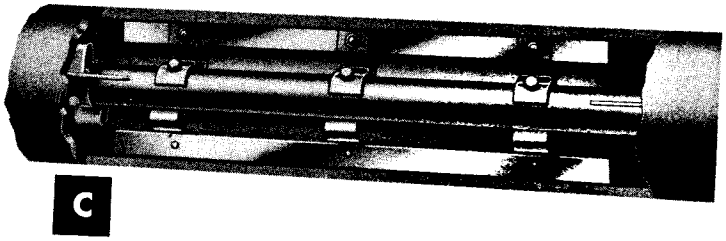



## Expansion valves

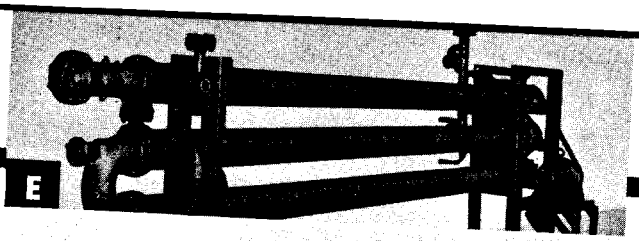
Hand-expansion valves still find a place in some larger systems. Globe-type ammonia valve **A** is built for hand expansion of refrigerants or for metering service. Needle point and fine-pitch stem threads allow close flow regulation. Freon hand-expansion valve **B** has multiple metal-diaphragm sealing. Inverted bucket trap **C** is used as an expansion valve in some systems with flooded evaporators; can also be applied for liquid-seal service.

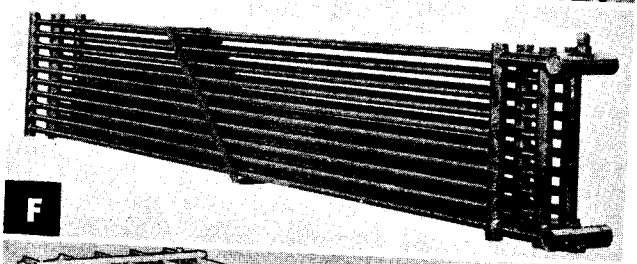
Thermostatic expansion valves **D**, **E** and **G**, are available for a number of different refrigerants to automatically control liquid flow into the evaporator. They are fitted with a remote thermal bulb clamped to the compressor suction line. Bulb actuates the valve, opening or closing it to increase or decrease refrigerant flow. Refrigerant distributor, **F**, gives equal feeding to multicircuit evaporators.




C

D


E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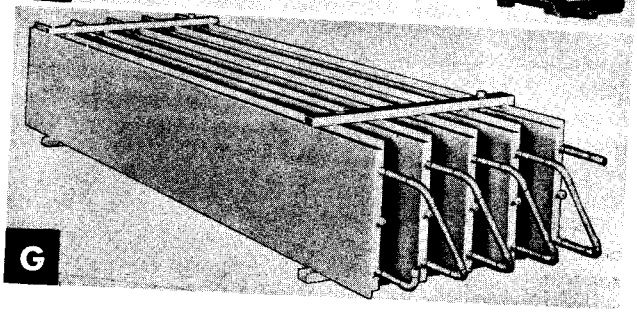
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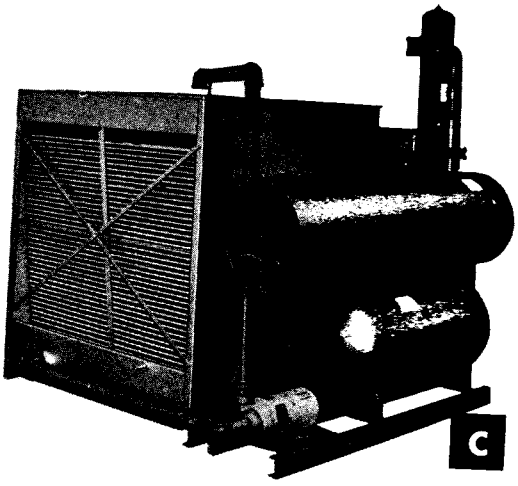
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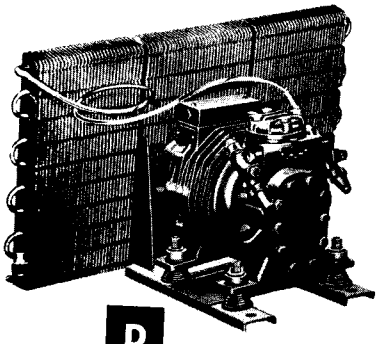
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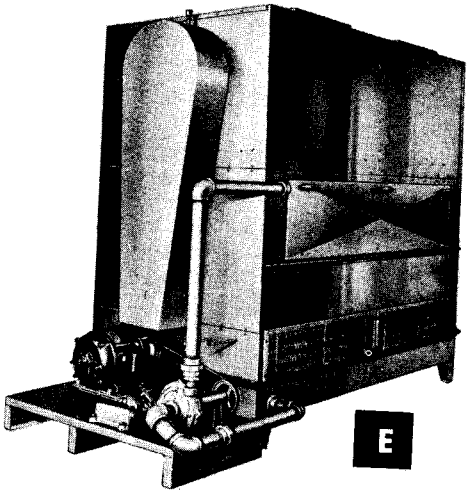
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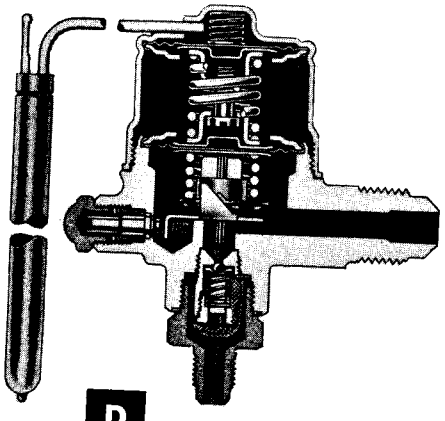
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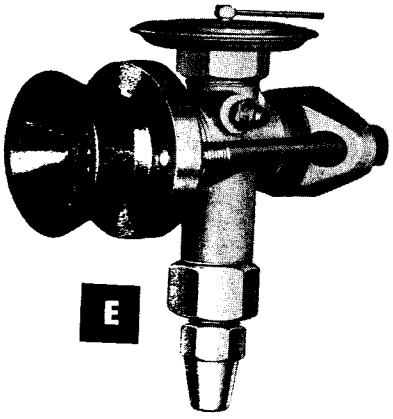
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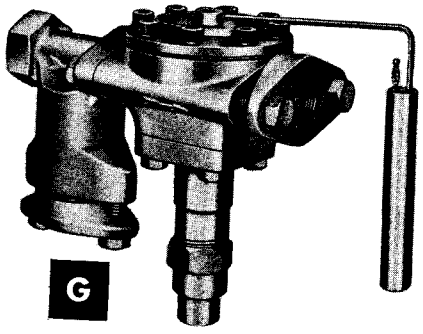
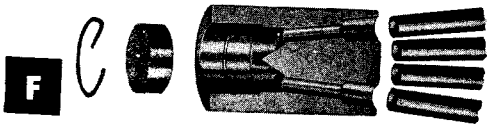

G


F

# Piping and fittings

Piping materials for refrigerants, brine and water include steel, wrought iron, malleable iron, cast iron, brass, copper and bronze. Piping is made to specifications approved by American Standards Association *Code for Pressure Piping*, ASA B31.1, table, *right*. Ammonia systems use ferrous pipe; types *K* and *L* copper tubing are often used for Freon.

Valves and fittings for refrigerant piping systems come in a large number of different types, some of which are shown here. Line shutoff valves must give safe, tight closure. Diaphragm packless valves **1**, with flare or solder connections, are popular for Freon. Ammonia valves **2** have extra-long packing glands to prevent leaks; backseating permits repacking under pressure. Relief valves **3** protect equipment from excessive pressure.

Because Freon refrigerants are good solvents, they remove sludge, chips, rust, etc, from inner walls of pipes and equipment. For this reason, filters **4** and **7** are often located in pipe lines. Driers **5** and **8** are packed with a dehydrating agent to remove moisture from the refrigerant. Economizers **6** and **9** use suction gas to subcool liquid refrigerant on its way to the expansion valve.

Other important fittings, for whose illustrations we do not have room, include oil separators, mufflers, liquid receivers, strainers, sight glasses, fusible plugs, check valves, receiver valves, compressor shutoff valves, purgers, etc.

## Materials for refrigeration piping

| *Material* | *Specification* | *Allowable stress, internal, psi* |
|---|---|---|
| Steel, seamless, Grade A | ASTM A53, A120, A106 A83, A179, A192 or API 5L | 12,000 |
| Steel, seamless, Grade B | ASTM A53, A106 or A210 | 15,000 |
| Steel, seamless alloy, Grades T18, T19 | ASTM A213 | 18,750 |
| Steel, electric-resistance welded, alloy, Grades T18, T19 | ASTM A249 | 15,900 |
| Steel, lap welded | ASTM A53, A106, A120 or API 5L | 9,000 |
| Steel, butt welded | ASTM A53 or A120 | 6,800 |
| Steel, electric-resistance welded | ASTM A135, A178, A214 or A226 | 10,200 |
| Wrought iron, lap welded | ASTM A72 or API 5L | 8,000 |
| Wrought iron, butt welded | ASTM A72 | 6,000 |
| Cast iron, pit cast | AWWA | 4,000 |
| Cast iron* | FSEC WW-P-421 | 6,000 |
| Brass, seamless, red brass | ASTM B43 | 4,700 |
| Copper, seamless | ASTM B42 | 4,000 |
| Copper tubing, seamless | ASTM B88 | 4,000 |

*Centrifugally cast or cast horizontally in green-sand molds

# Controls

A variety of control devices are required for industrial systems since they have to meet many different load situations.

Capacity control **10** is the pneumatic step type; it provides: (1) on-off operation of steps in sequence (2) positive prevention of starting more than one compressor at a time after night shutdown or current failure (3) manual or automatic changing of operating sequence to equalize wear. Some compressors have pockets for varying unit capacity.

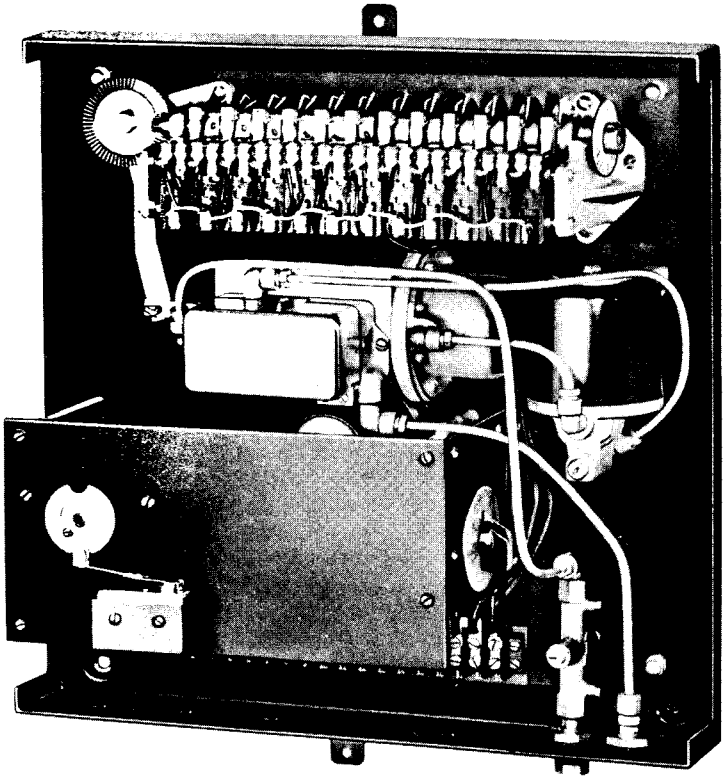
Pressure controller **11** starts and stops the compressor in response to machine suction pressure. This provides good control, especially when load is constant, or nearly so.

Condensing-water regulating valve **12**, installed in the condenser water-supply line, is actuated by high-side pressure or temperature. When pressure or temperature rises, the valve opens wider, admitting more water to condenser. Spring closes valve when temperature or pressure falls.

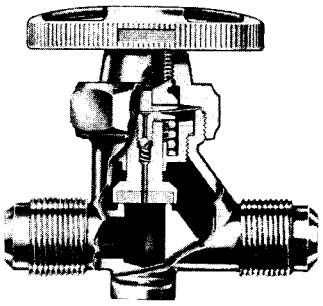
Evaporator pressure regulator **13** is a spring-loaded pressure-operated valve installed in suction line to maintain the evaporator pressure at a constant value. It prevents coil frosting, chiller freeze-ups, etc.

Solenoid stop valves **14** provide a means of stopping refrigerant gas or liquid flow in response to action of thermostat or pressure control. They control flow to expansion valves, coils and compressors.

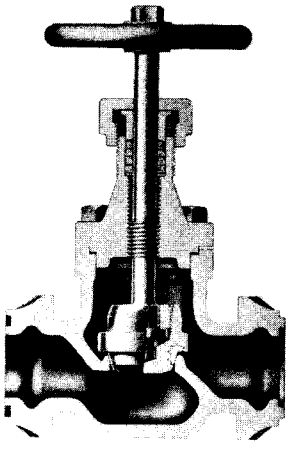
Float control **15** has a mercury switch for high or low liquid-level alarm, pump control on surge drums, receivers, tanks, etc. Room thermostat **16** opens or closes an electric circuit in response to room-temperature change, can actuate a relay to start compressor.



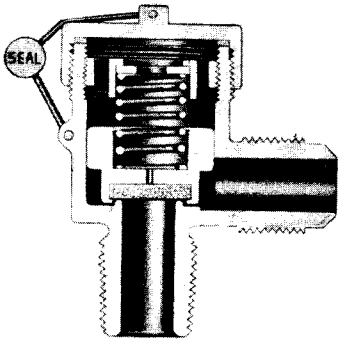
**10 PNEUMATIC STEP-CONTROL**



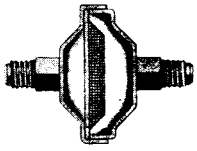
1 PACKLESS VALVE



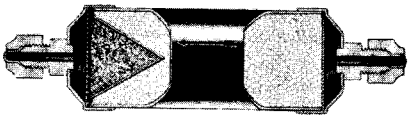
2 AMMONIA VALVE



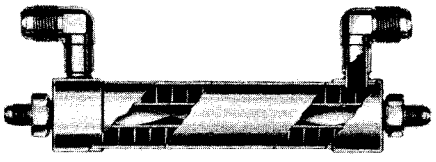

3 RELIEF-VALVE



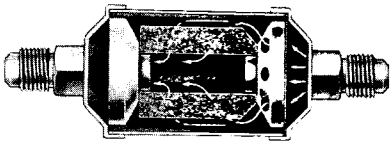
4 FILTER-STRAINER



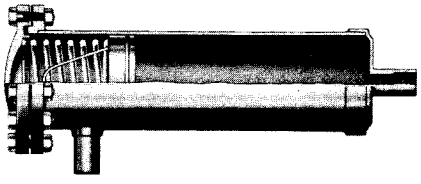
5 NONREFILLABLE DRIER



6 FIN-TYPE ECONOMIZER

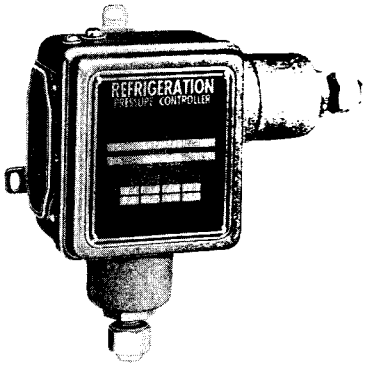


7 WOOL-FIBER FILTER

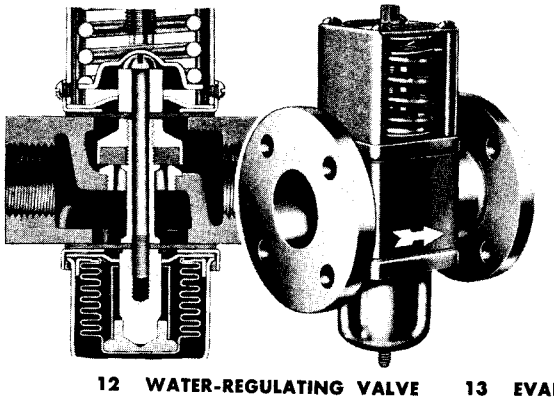


8 REPLACEABLE DRIER

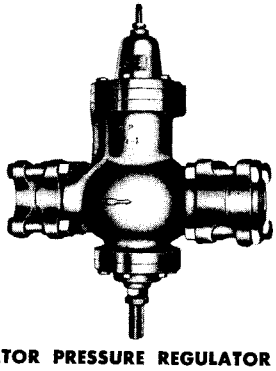
9 COIL-TYPE ECONOMIZER



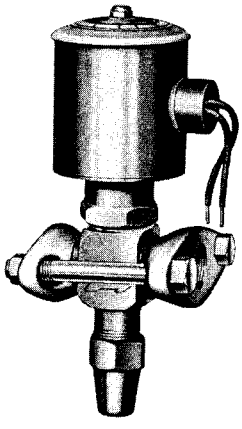

11 PRESSURE CONTROLLER

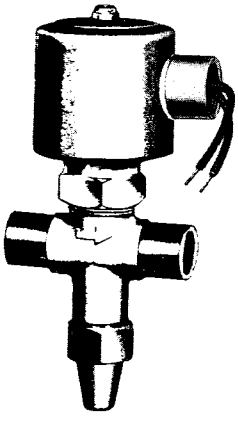


12 WATER-REGULATING VALVE

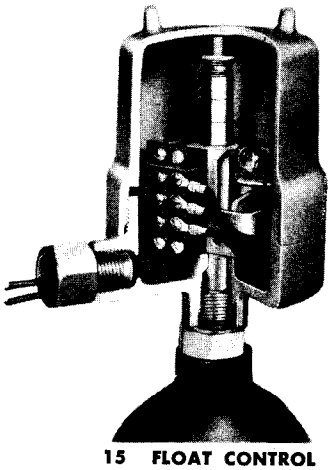


13 EVAPORATOR PRESSURE REGULATOR

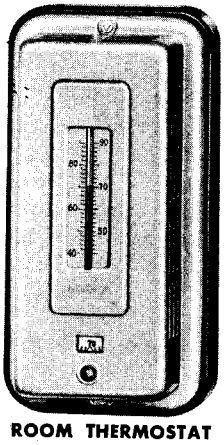




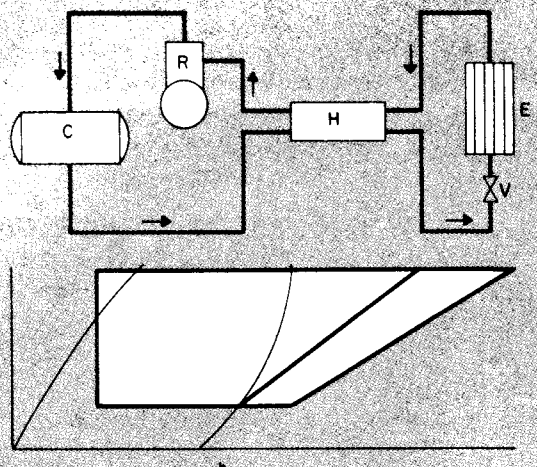
14 SOLENOID VALVES: AMMONIA AND FREON



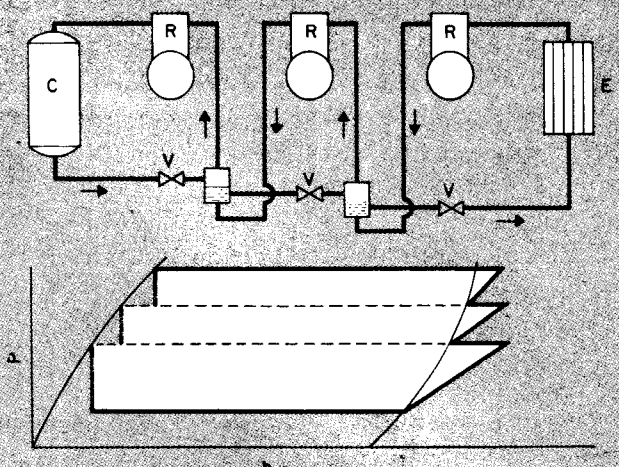
15 FLOAT CONTROL



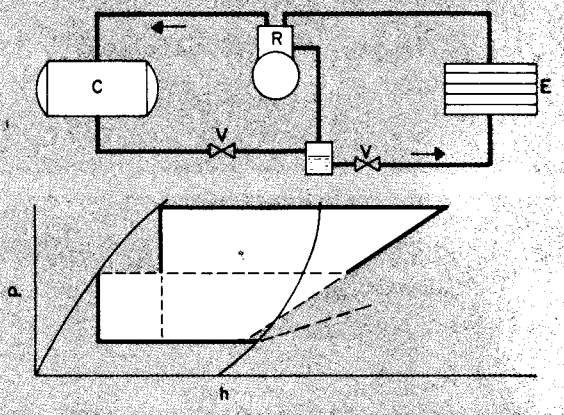
16 ROOM THERMOSTAT



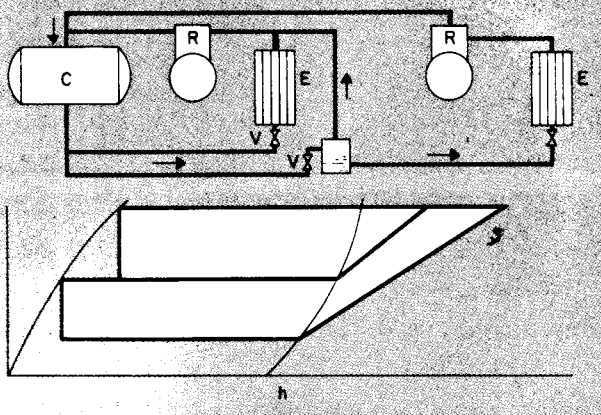

**SUBCOOLING** the liquid refrigerant is a simple way to secure greater refrigerating effect. The suction gas is often used




**COMPOUND COMPRESSION** uses two or more stages between evaporator, condenser; requires less power input for operation




**DUAL OR MULTIPLE-EFFECT** compression has one compressor to handle suction gas at two different pressures; is economical




**SECTIONALIZING** is way of operating two or more evaporators at different pressures and temperatures without too much loss

C = *condenser* E = *evaporator* H = *heat exchanger* R = *refrigeration compressor* V = *expansion or control valve*

# Refrigeration applications

End purpose of every refrigeration system is production of a lower temperature by transfer of heat from a place where it is not wanted to a place it is unobjectionable. And many different schemes are used to improve efficiency.

**Subcooling** of the refrigerant liquid on way to the expansion valve can be produced by use of either water, or suction gas leaving the evaporator. The liquid is subcooled when its temperature is less than that corresponding to its pressure.

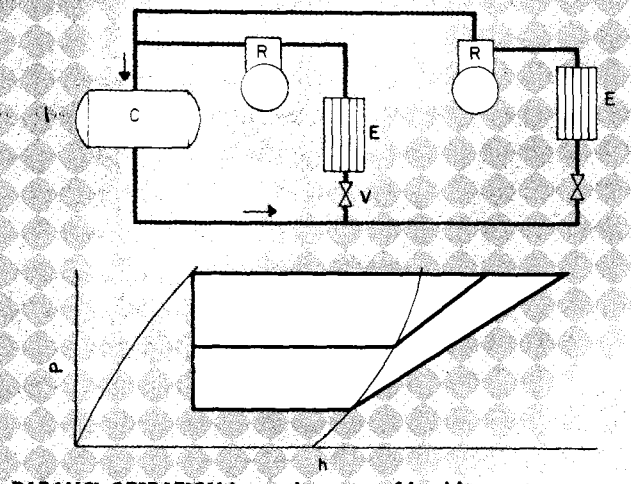
Advantages of subcooling include (1) reduction of some of the flash loss in the expansion valve, (2) an increase in refrigerating effect obtained in the system. Also compressor and condenser loads are reduced and superheating of the suction gas between the evaporator and compressor is prevented or minimized. Though subcooling by water is possible, use of suction gas is more common.

**Compounding** consists of using two or more stages of compression between the evaporator and condenser. Usually two separate compressors are used, one high-pressure and one low-pressure unit, but other arrangements are possible. Less power input is needed in compound systems than in the single-stage systems operating over the same temperature and pressure range.

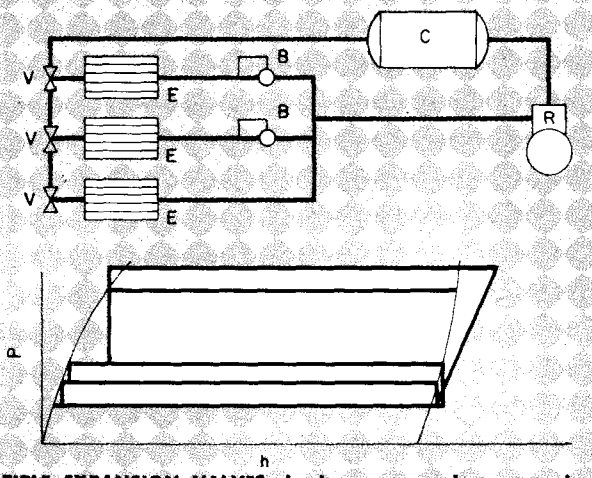
Though power saving is the principal advantage of compounding, the possibility of cooling liquid refrigerant with gas going to the high-pressure compressor suction and cooling the low-pressure discharge gas in a water-cooled intercooler offers further economies. Compounding is widely applied to low-temperature systems using reciprocating compressors. In these jobs the low-pressure unit is often called a booster compressor. It handles large volumes of low-pressure refrigerant gas leaving the evaporator.

**Dual or multiple-effect** compressors handle suction gas at two different pressures in the same cylinder. Lower-pressure gas is drawn in during the normal suction stroke. It is compressed and near the end of the stroke the piston uncovers a port through which the higher pressure gas is admitted. The piston completes its stroke, compressing all gas in the cylinder and discharging to the condenser.

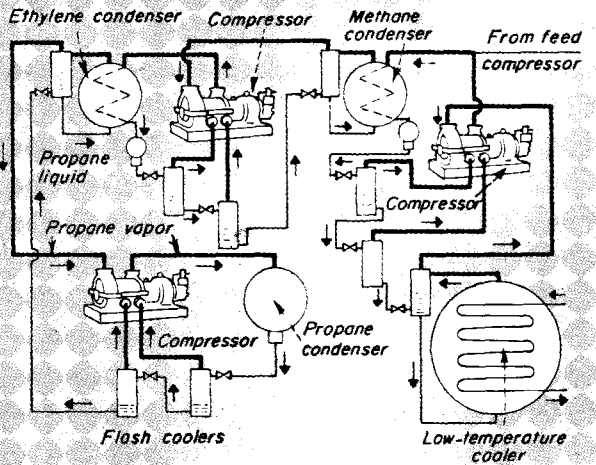
Multiple-effect compression is not the same as compounding because there is no chance for intercooling, together with the attendant savings. Instead, multiple-effect compression is like having two separate compressors, each operating at a different suction pressure but discharging to a single




**PARALLEL OPERATION is another way of hooking up two or more evaporators for different suction pressures and temperatures**




**MULTIPLE EXPANSION VALVES, backpressure valves can give close control of two or more different-pressure evaporators**




**CASCADE SYSTEM shown uses centrifugal compressors for ultra-low temperatures in liquefied-gas storage, has high efficiency**

## Theoretical compressor power for a Freon-12 plant*

**Loads: 10 tons at 44 F, 30 tons at 34 F, and 20 tons at 24 F**

| Type of system | Hp | Reduction from maximum, % |
|---|---|---|
| **One compressor:** | | |
| All evaporators at same temperature | 53.6 | 0.0 |
| Individual exp valves and backpressure valves | 52.4 | 2.2 |
| Multiple exp valves and backpressure valves | 51.7 | 3.5 |
| **Two compressors (one dual-effect type):** | | |
| Individual expansion valves | 47.7 | 11.0 |
| Multiple expansion valves | 45.9 | 14.4 |
| **Three individual compressors:** | | |
| Individual expansion valves | 46.4 | 13.4 |
| Multiple expansion valves | 44.7 | 16.6 |
| **Compound compressors and intercoolers:** | | |
| Individual expansion valves | 46.0 | 14.2 |
| Multiple expansion valves | 44.5 | 17.0 |

*From "Refrigeration and Air Conditioning," by Jordan and Priester, Prentice-Hall, Inc

condenser. Some designs of dual-effect compressors have clearance pockets to provide capacity control.

The principal advantage of multiple-effect compression is a reduction in system power costs. Many ice plants use it for this purpose. It also is a convenient means of operating two evaporators at different temperatures.

**Sectionalizing** is one method of operating two or more evaporators at different pressures and temperatures without the necessity of compressing the gas from higher-pressure evaporators through a range greater than required. As shown in the equipment diagram above, two compressors may be used, one for the low-pressure evaporator and one for the high-pressure evaporator. Both discharge to a common condenser. Flash vapor formed in the low-pressure expansion valve is separated in a flash chamber, from where it flows to the suction of the high-pressure evaporator.

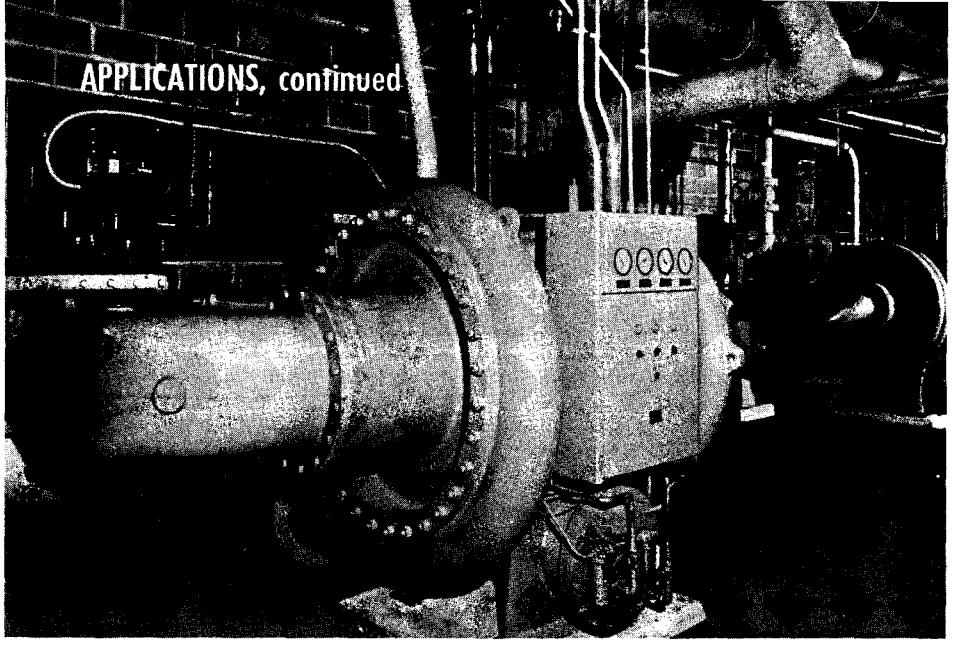
**Parallel operation** is another method of providing for two or more evaporators using different suction pressures and temperatures. As shown, each evaporator has its own expansion valve and compressor, but there is a common condenser. The compressors and their evaporators operate independently except for using the common condenser. Either dry-type evaporators, p 82, or flooded-type, may be adopted. In latter not all the refrigerant evaporates, the vapor-liquid mixture flowing to a surge drum from which vapor is drawn off by the compressor and liquid is recirculated to the evaporator.

Multiple-expansion valves in conjunction with backpressure valves are another means of providing for two or more evaporators at different pressures and temperatures. With this hookup the evaporators shown have a common suction pressure, corresponding to that of the lowest-temperature evaporator. The backpressure valves in the two higher-temperature evaporators maintain the higher coil pressures required in them. Table, *above right,* shows the power input savings possible with a fixed load and various hookups.

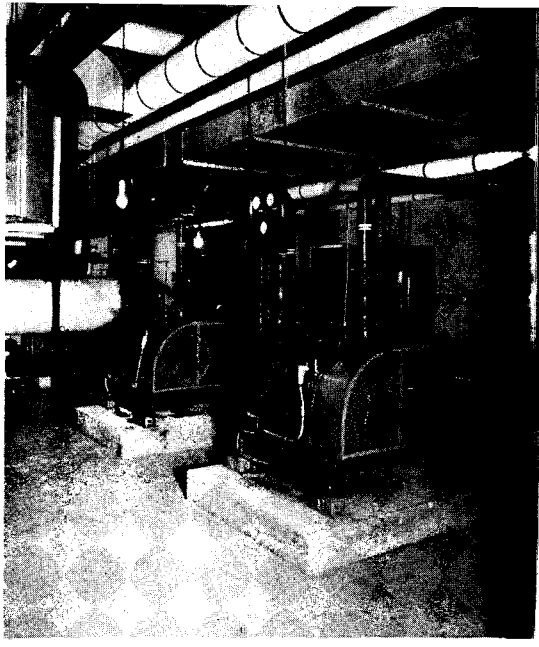
**System size** is a definite factor in the arrangement chosen. Large systems, where power savings may be considerable, often use one or more of the arrangements shown. Others, not shown here, are also used, depending on the specific requirements of the process served by the system.

In small systems the power savings possible may be insignificant because the power input required is small to start with. So one or more special controls are used instead of a multiple-compressor hookup. Typical controls include thermostatic expansion valves, backpressure valves, float switches, suction-pressure regulators, etc.

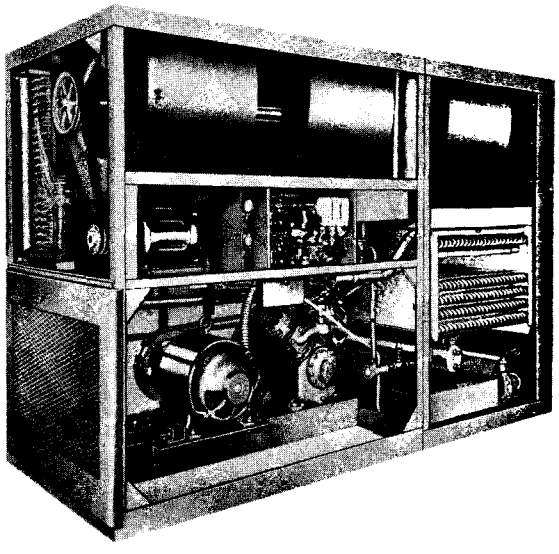
**Extremely low temperatures** may be produced in a number of ways. One popular method, called the cascade system, uses a series of refrigerants having progressively lower boiling points. As shown above, one refrigerant serves as the coolant to condense the refrigerant gas with the next lower boiling temperature. Cascading is generally applied at temperatures below about −135 F, but with newer refrigerants becoming available it is possible that this temperature might be lowered in the near future.



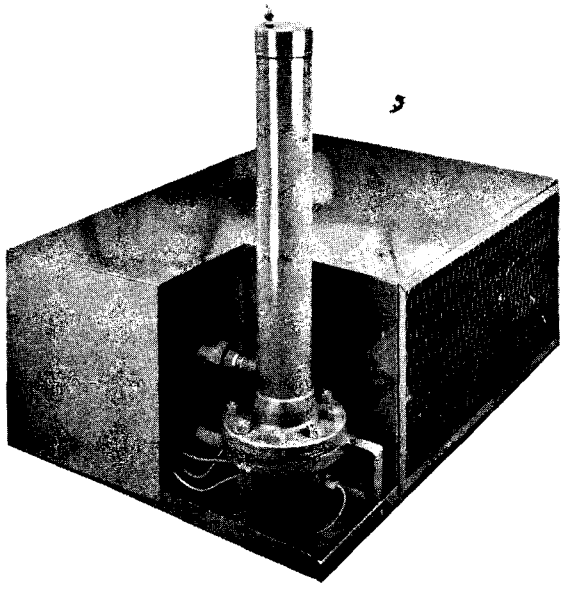
AIR-CONDITIONING installations use centrifugal compressors for the larger loads. A wide range of sizes permits multiple installation to give the desired capacity



RECIPROCATING compressors here serve an air-conditioning system in a hospital



UNIT AIR CONDITIONER contains Freon-12 compressor, condenser, evaporator controls. Fans blow conditioned air to rooms



SOLVENT COOLER for dry-cleaning plants uses a hermetically sealed compressor, is fitted with solvent circulating pump

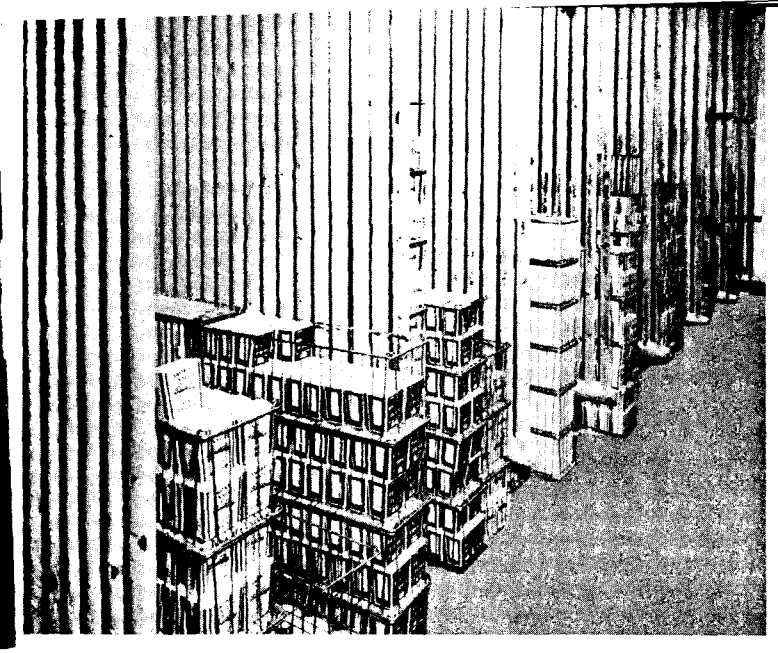
Without going too far off the beam we can classify refrigeration applications in seven broad categories—air conditioning, food processing and storage, ice making, industrial processes, medical, heat pump and miscellaneous. Illustrations on these two pages show units for a number of these services.

**Air conditioning** is probably the most talked about application, with the heat pump next. Yet our lives are affected in a great many other ways by refrigeration — someone has even said from the cradle to the grave, and he's probably correct.

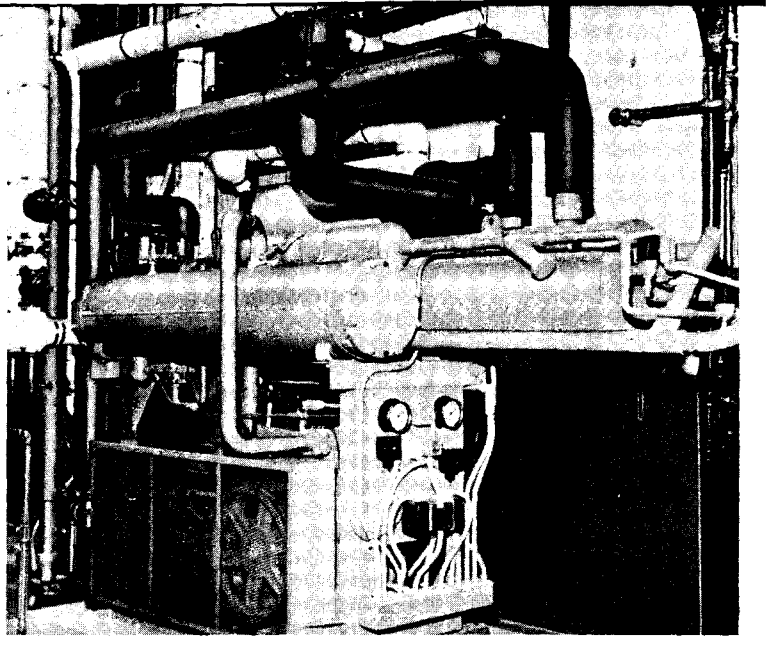
From the tiny room air conditioner to the 2000-ton centrifugal serving an entire building, air conditioning uses millions of tons of refrigeration capacity. Unit conditioners available today are compact, noisefree devices requiring a minimum of installation work. Operation, after the unit is turned on, is usually automatic. Though there is no definite capacity limitation on unitary-type equipment, capacities above about 12,000 cfm or about 40 tons of refrigeration are believed to be more economically handled by field-assembled equipment. Multiple installations of unit conditioners are often economical for larger air flows or tonnages where zoning is desired or air ducts must be kept to a minimum.

The next step up in capacity from unitary equipment for air conditioning is to the central-type system using field-assembled units serving, usually, more than one room or area, with separate control for each room or area. Ducts generally connect the apparatus with the various rooms, the refrigeration equipment, fans, coils, etc, being in the building basement or another space separate from the conditioned rooms.

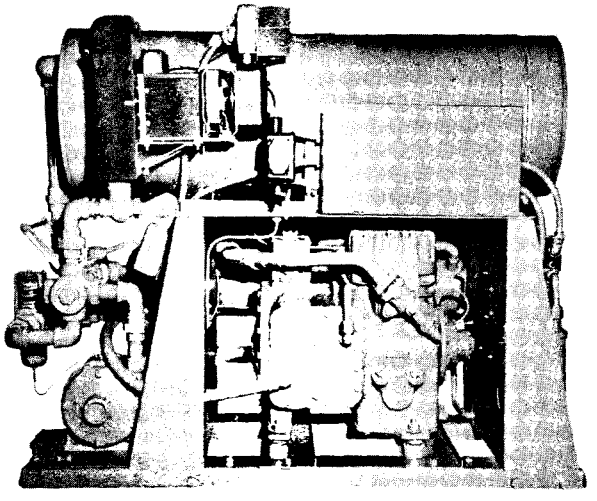
As with unit conditioners, there is no definite point at which one type of equipment is used in preference to another. But current practice uses reciprocating compressors and steam-jet units in capacities to about 400 tons, with absorption units running up to



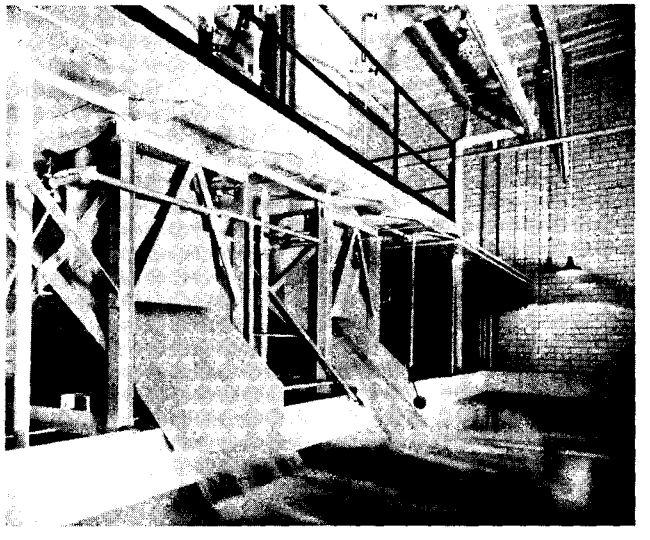
**FOOD PROCESSING** is another big user of refrigeration. Shown here is an ice-cream storage room fitted with vertical coils



**LIQUID CHILLER** of packaged design has a dry-expansion type chiller on same base with reciprocating compressor, controls



**HEAT PUMPS** use refrigeration principles to heat or cool, are finding jobs in some industrial and commercial installations



**ICE-MAKING MACHINE** is used here in conjunction with storage tank, meets peak loads by cooling makeup water entering tank

somewhat over 700 tons. In systems of over 25 tons capacity we are likely to find reciprocating, absorption, steam-jet or centrifugal, but except for reciprocating units, the representation is rather spotty. Over about 400 tons, centrifugal, absorption and steam-jet units predominate in air conditioning.

**Food processing** — manufacture, storage and transportation—takes a big chunk of tonnage. While reciprocating compressors are popular in cold storage, frozen foods, packing and manufacturing, other types of units are also used. In a given application the choice of unit type is a function of the load, temperature required, and a number of other important governing factors.

**Ice making,** one of the earliest applications of mechanical refrigeration, is almost solely in the province of reciprocating compressors. With the widespread use of domestic refrigerators, the emphasis in ice making has shifted somewhat from the can-ice plant to cubed and sized ice. Today, block-ice manufacturers produce about 800,000 tons annually of clear solid cubes, using either automatic or semi-automatic machines. In recent years much study has been given the manufacture of cubes of various sizes and types, resulting in the design of a variety of specialized machines for cube production.

**Industrial processes** might be called the unknown soldiers of refrigeration because so many products require refrigeration at one stage or another during manufacture or preparation for it. A few of the processes using refrigeration include metal treatment, testing, chemical production, oil refining, rubber manufacture, building construction, natural gas, etc. Temperatures vary over the entire range, requiring many different units.

**Medical and surgical** applications of refrigeration are growing continually—from blood-plasma manufacture to shock prevention and use as an anesthetic. The Salk vaccine is the latest in a long list of aids to health produced by some use of refrigeration equipment.

## Physical properties of common refrigerants

**Based on standard-ton conditions: evaporation at 5F, condensation at 86F**

| | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | OPERATING DATA | | | | | | | | | | | | | | | SAFETY DATA | | | | | | | |
| Name of refrigerant | Chemical symbol(1) | Evaporator temperature range (2) | Boiling point, F (atmospheric) | Freezing point, F (atmospheric) | Critical temp, F | Condensing (head) pressure, at 86 F, psi gage (3) | Evaporation (suction) pressure at 5 F, psi gage (3) | Net refrig effect, (86 F to 5 F) Btu per lb | Refrigerant flow, (86 F to 5 F) lb per min per ton | Liquid refrig flow (86 F to 5 F) cu in. per min per ton | Compressor displacement (86 F to 5 F) cfm per ton | Hp per ton | Type of compressor (4) | Compressor cooling | Safety code group(5) | Low-side min test press. psi gage(6) | High-side min test press. psi gage (6) | Concentration in air to form flammable or explosive mix, % by volume (7) | Kills or seriously injures when in air: Exposure time, hr | Kills or seriously injures when in air: % by volume concentration | Kills or seriously injures when in air: Lb per 1000 cu ft of air | Mix with lube oil? | Odor? (8) |
| Ammonia | $NH_3$ | L–H | –28.0 | –107.9 | 271.2 | 154.5 | 19.6 | 474.6 | 0.421 | 19.6 | 3.46 | 0.98 | Rec | Water | 2 | 150 | 300 | 16–25 | 1/2 | 0.5 | 0.25 | No | Yes |
| Carbon dioxide | $CO_2$ | L, M | –109.3 | –69.9 | 87.8 | 1028.3 | 316.8 | 55.5 | 3.61 | 167.0 | 0.96 | 1.83 | Rec | Water | 1 | 1000 | 1500 | N | 1/2–1 | 29 | 33 | No | No |
| Dielene | $C_2H_2Cl_2$ | H | 118.0 | –70.0 | 470.0 | 15.8* | 28.3* | 114.3 | 1.75 | 38.3 | 111.2 | 0.97 | Cen | Water | 2 | 30 | 30 | 5.6–11.4 D | 1 | 2 | 5 | Yes | Weak |
| Ethyl chloride | $C_2H_5Cl$ | M, H | 54.5 | –217.7 | 369.0 | 12.4 | 20.5* | 142.3 | 1.41 | 44.4 | 22.62 | 0.91 | Rot. | Air | 2 | 50 | 60 | 3.7–12 D | 1 | 4 | 7 | Yes | Yes |
| Freon–11 | $CCl_3F$ | H | 74.7 | –168.0 | 388.4 | 3.6 | 24.0* | 67.5 | 2.96 | 56.0 | 36.3 | 0.94 | Rot. Cen | Water | 1 | 30 | 30 | N, D | 2 | 10 | 35 | Yes | No |
| Freon–12 | $CCl_2F_2$ | M, H | –21.6 | –247.0 | 233.0 | 93.2 | 11.8 | 51.1 | 3.91 | 83.8 | 5.81 | 1.01 | Rec-Rot. | W or A | 1 | 140 | 235 | N, D | 2 | 28 | 90 | Yes | No |
| Freon–21 | $CHCl_2F$ | M, H | 48.0 | –211.0 | 353.3 | 16.5 | 19.3* | 89.4 | 2.24 | 45.8 | 20.46 | 0.93 | Rot. | Air | 1 | 40 | 70 | N | 1/2 | 10 | 27 | Yes | No |
| Freon–22 | $CHClF_2$ | U, L | –41.4 | –256.0 | 204.8 | 159.8 | 28.3 | 69.3 | 2.89 | 68.1 | 3.60 | 1.02 | Rec | Water | 1 | 150 | 300 | N, D | – | – | – | Yes | No |
| Freon–113 | $C_2Cl_3F_3$ | H | 117.6 | –31.0 | 417.4 | 13.9* | 27.9* | 53.7 | 3.73 | 66.4 | 100.9 | 0.98 | Cen | Water | 1 | 30 | 30 | N, D | 1 | 5 | 23 | Yes | No |
| Freon–114 | $C_2Cl_2F_4$ | M, H | 38.4 | –137.0 | 294.3 | 22.0 | 16.1* | 43.1 | 4.64 | 89.3 | 19.59 | 0.99 | Rot. | Air | 1 | 50 | 50 | N, D | 2 | 20 | 90 | Yes | No |
| Isobutane | $(CH_3)_3CH$ | M, H | 10.3 | –229.0 | 272.7 | 44.8 | 3.3* | 111.5 | 1.79 | 91.1 | 11.50 | 1.08 | Rec-Rot. | W or A | 3 | 70 | 130 | 1.8–8.4 | – | – | – | Yes | Weak |
| Methyl chloride | $CH_3Cl$ | M, H | –10.8 | –144.0 | 289.4 | 80.0 | 6.5 | 150.2 | 1.33 | 40.9 | 5.95 | 1.02 | Rec-Rot. | W or A | 2 | 120 | 210 | 8.1–17.2 D | 2 | 2 | 2.5 | Yes | Weak |
| Methylene chloride | $CH_2Cl_2$ | H | 103.6 | –142.0 | 421.0 | 8.4* | 27.4* | 134.6 | 1.49 | 30.9 | 74.3 | 0.97 | Cen | Water | 1 | 30 | 30 | N, D | 1/2 | 5 | 11 | Yes | Weak |
| Sulfur dioxide | $SO_2$ | M, H | 14.0 | –103.9 | 314.8 | 51.8 | 5.9* | 142.8 | 1.40 | 28.6 | 9.10 | 0.97 | Rec-Rot. | W or A | 2 | 85 | 170 | N | 5 min | 0.7 | 1.2 | No | Yes |
| Water (40 F & 86 F) | $H_2O$ | H | 212.0 | 32.0 | 706.1 | 28.7* | 29.7* | 1025.3 | 0.195 | 5.4 | 476.6 | 1.13 | Cen-Jet | Water | – | – | – | N | – | – | – | No | No |

(1) N–Nitrogen, H–Hydrogen, C–Carbon, Cl–Chlorine, F–Fluorine, S–Sulfur
(2) U–Ultra-low: –130 to –75 F, L–Low: –75 to 0 F, M–Medium: 0 to 30 F, H–High: over 30 F, (3)* inches of mercury vacuum, (4) Rec–Reciprocating. Cen–Centrifugal, Rot.–Rotary, (5) ASRE Std 15-53: 1–Used generally with minor limitations, 2–Used generally with strict limitations, 3–Prohibited in all but industrial occupancies (and commercial laboratories in unit systems containing not over 6 lb); see Standard for exact limitations for all refrigerants.
(6) From ASRE Std 15-53: (7) N–nonflammable, except slightly flammable Freon-21; D–Decomposition products from heat of flame are highly toxic.
(8) Decomposition products of Freons, etc, have pungent odors.

# Refrigerants and brines

There is no perfect refrigerant, nor is there one refrigerant which is usable for the complete cooling range required in industrial and commercial applications. So we find a large number of refrigerants in use today.

**Properties.** Table above summarizes properties of many common refrigerants. Note that so-called safety factors — toxicity, irritant properties, flammability etc, play important parts in refrigerant choice, especially where large numbers of people might be exposed to the gas during system failure. With ever-widening use of air conditioning, we find older refrigerants like ammonia, carbon dioxide and sulfur dioxide decreasing in use for smaller units. They have been replaced by members of the Freon family—refrigerants made from hydrocarbons.

Physical properties of refrigerants are also important because they too affect selection. Boiling and freezing points and critical temperatures set rough limits on the kinds of jobs for which refrigerants are suited. "Heat" or enthalpy properties, tables, *facing page,* determine the amount of refrigerant that must be circulated for a given capacity and are valuable in both system design and analysis.

Using refrigerants that must be condensed at high pressures means heavy construction for the compressor, piping and condenser, increasing system cost.

Some Freons are called *vacuum refrigerants* because they exist as liquid at normal atmospheric temperature and pressure. To produce refrigeration temperatures in an evaporator, these refrigerants must be vaporized at pressures below atmospheric.

Refrigerating-equipment size depends on refrigerant density and the ability of the liquid to absorb heat. These two factors can be combined into one index—piston displacement—which tells how many cubic feet of refrigerant must be handled each minute to produce one ton of refrigeration.

**Lubrication** of a refrigeration unit depends on compressor design, cooling method, refrigerant used and operating conditions. Table, *right,* gives the viscosity ranges of lubricants commonly used with various types of compressors and refrigerants. Usual aim is to use the oil having the lowest viscosity that gives the required sealing with the refrigerant used at the temperature and pressure ranges met in the system.

Oil properties, which must be considered in practice, include pour test and cloud point, volatility, flash and fire points, moisture, stability and solubility of oil and refrigerant. Pour and cloud points may have little effect in normal air-conditioning applications, but in low-temperature units they may greatly influence lubricant choice. Oil volatility should be chosen so the lubricant does not vaporize at pressures and temperatures met in the high side of the system.

Some refrigerants having high specific-heat ratios have high compression temperatures, leading to carbonization of lubricants with low flash and fire points. To prevent expansion-valve freeze-ups, refrigeration oils should have a low moisture content. Stability against oxidation and heat are also important. Solubility characteristics,

# Pressure-enthalpy properties of ammonia and Freon-12

## SATURATED AMMONIA

(All values are per lb of refrigerant)

| Temp F | Psia | Psig | Liquid density lb/cu ft | Vapor sp vol cu ft/lb | Enthalpy Sat. liquid | Enthalpy Evap | Enthalpy Sat. vapor |
|---|---|---|---|---|---|---|---|
| -40 | 10.41 | 8.7* | 43.08 | 24.86 | 0.0 | 597.6 | 597.6 |
| -30 | 13.90 | 1.6* | 42.65 | 18.97 | 10.7 | 590.7 | 601.4 |
| -20 | 18.30 | 3.6 | 42.22 | 14.68 | 21.4 | 583.6 | 605.0 |
| -10 | 23.74 | 9.0 | 41.78 | 11.50 | 32.1 | 576.4 | 608.5 |
| 0 | 30.42 | 15.7 | 41.34 | 9.116 | 42.9 | 568.9 | 611.8 |
| 5 | 34.27 | 19.6 | 41.11 | 8.150 | 48.3 | 565.0 | 613.3 |
| 10 | 38.51 | 23.8 | 40.89 | 7.304 | 53.8 | 561.1 | 614.9 |
| 20 | 48.21 | 33.5 | 40.43 | 5.910 | 64.7 | 553.1 | 617.8 |
| 30 | 59.74 | 45.0 | 39.96 | 4.825 | 75.7 | 544.8 | 620.5 |
| 40 | 73.32 | 58.6 | 39.49 | 3.971 | 86.8 | 536.2 | 623.0 |
| 50 | 89.19 | 74.5 | 39.00 | 3.294 | 97.9 | 527.3 | 625.2 |
| 60 | 107.6 | 92.9 | 38.50 | 2.751 | 109.2 | 518.1 | 627.3 |
| 70 | 128.8 | 114.1 | 38.00 | 2.312 | 120.5 | 508.6 | 629.1 |
| 80 | 153.0 | 138.3 | 37.48 | 1.955 | 132.0 | 498.7 | 630.7 |
| 86 | 169.2 | 154.5 | 37.16 | 1.772 | 138.9 | 492.6 | 631.5 |
| 90 | 180.6 | 165.9 | 36.95 | 1.661 | 143.5 | 488.5 | 632.0 |
| 100 | 211.9 | 197.2 | 36.40 | 1.419 | 155.2 | 477.8 | 633.0 |
| 110 | 247.0 | 232.3 | 35.84 | 1.217 | 167.0 | 466.7 | 633.7 |
| 120 | 286.4 | 271.7 | 35.26 | 1.047 | 179.0 | 455.0 | 634.0 |

* Inches of mercury below one standard atmosphere (29.92 in.)

## SATURATED FREON-12

| Temp F | Psia | Psig | Liquid density lb/cu ft | Vapor sp vol cu ft/lb | Enthalpy Sat. liquid | Enthalpy Evap | Enthalpy Sat. vapor |
|---|---|---|---|---|---|---|---|
| -40 | 9.317 | 10.96* | 0.01057 | 3.911 | 0.00 | 73.50 | 73.50 |
| -30 | 12.02 | 5.45* | 0.0107 | 3.088 | 2.03 | 72.67 | 74.70 |
| -20 | 15.28 | 0.58 | 0.0108 | 2.474 | 4.07 | 71.80 | 75.87 |
| -10 | 19.20 | 4.50 | 0.0109 | 2.003 | 6.14 | 70.91 | 77.05 |
| 0 | 23.87 | 9.17 | 0.0110 | 1.637 | 8.25 | 69.96 | 78.21 |
| 5 | 26.51 | 11.81 | 0.0111 | 1.485 | 9.32 | 69.47 | 78.79 |
| 10 | 29.35 | 14.65 | 0.0112 | 1.351 | 10.39 | 68.97 | 79.36 |
| 20 | 35.75 | 21.05 | 0.0113 | 1.121 | 12.55 | 67.94 | 80.49 |
| 30 | 43.16 | 28.46 | 0.0115 | 0.939 | 14.76 | 66.85 | 81.61 |
| 40 | 51.68 | 36.98 | 0.0116 | 0.792 | 17.00 | 65.71 | 82.71 |
| 50 | 61.39 | 46.69 | 0.0118 | 0.673 | 19.27 | 64.51 | 83.78 |
| 60 | 72.41 | 57.71 | 0.0119 | 0.575 | 21.57 | 63.25 | 84.82 |
| 70 | 84.82 | 70.12 | 0.0121 | 0.493 | 23.90 | 61.92 | 85.82 |
| 80 | 98.76 | 84.06 | 0.0123 | 0.425 | 26.28 | 60.52 | 86.80 |
| 86 | 107.9 | 93.2 | 0.0124 | 0.389 | 27.72 | 59.65 | 87.37 |
| 90 | 114.3 | 99.6 | 0.0125 | 0.368 | 28.70 | 59.04 | 87.74 |
| 100 | 131.6 | 116.9 | 0.0127 | 0.319 | 31.16 | 57.46 | 88.62 |
| 110 | 150.7 | 136.0 | 0.0129 | 0.277 | 33.65 | 55.78 | 89.43 |
| 120 | 171.8 | 157.1 | 0.0132 | 0.240 | 36.16 | 53.99 | 90.15 |

## SUPERHEATED AMMONIA

(V—specific volume; H—enthalpy)

| Total temp, F | Absolute pressure, psia (saturation temperature, F) 20 (-16.64) V | H | 30 (-0.57) V | H | 40 (11.66) V | H | 140 (74.79) V | H | 170 (86.29) V | H | 200 (96.34) V | H |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| -10 | 13.74 | 610.0 | – | – | – | – | – | – | – | – | – | – |
| 0 | 14.09 | 615.5 | 9.250 | 611.9 | – | – | – | – | – | – | – | – |
| 20 | 14.78 | 626.4 | 9.731 | 623.5 | 7.203 | 620.4 | – | – | – | – | – | – |
| 40 | 15.45 | 637.0 | 10.20 | 634.6 | 7.568 | 632.1 | – | – | – | – | – | – |
| 60 | 16.12 | 647.5 | 10.65 | 645.5 | 7.922 | 643.4 | – | – | – | – | – | – |
| 80 | 16.78 | 658.0 | 11.10 | 656.2 | 8.268 | 654.4 | 2.166 | 633.8 | – | – | – | – |
| 100 | 17.43 | 668.5 | 11.55 | 666.9 | 8.609 | 665.3 | 2.288 | 647.8 | 1.837 | 641.9 | 1.520 | 635.6 |
| 150 | 19.05 | 694.7 | 12.65 | 693.5 | 9.444 | 692.3 | 2.569 | 679.9 | 2.081 | 675.9 | 1.740 | 671.8 |
| 200 | 20.66 | 721.2 | 13.73 | 720.3 | 10.27 | 719.4 | 2.830 | 709.9 | 2.303 | 706.9 | 1.935 | 703.9 |
| 250 | – | – | 14.81 | 747.5 | 11.08 | 746.8 | 3.080 | 739.2 | 2.514 | 736.8 | 2.118 | 734.5 |

## SUPERHEATED FREON-12

| Total temp, F | Absolute pressure, psia (saturation temperature, F) 20 (-8.2) V | H | 40 (25.9) V | H | 60 (48.7) V | H | 120 (93.4) V | H | 140 (104.5) V | H | 160 (114.5) V | H |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 20 | 2.060 | 81.14 | – | – | – | – | – | – | – | – | – | – |
| 30 | 2.107 | 82.55 | 1.019 | 81.76 | – | – | – | – | – | – | – | – |
| 40 | 2.155 | 83.97 | 1.044 | 83.20 | – | – | – | – | – | – | – | – |
| 50 | 2.203 | 85.40 | 1.070 | 84.65 | 0.690 | 83.83 | – | – | – | – | – | – |
| 60 | 2.250 | 86.85 | 1.095 | 86.11 | 0.708 | 85.33 | – | – | – | – | – | – |
| 80 | 2.343 | 89.78 | 1.144 | 89.09 | 0.743 | 88.35 | – | – | – | – | – | – |
| 100 | 2.437 | 92.75 | 1.194 | 92.09 | 0.778 | 91.41 | 0.357 | 89.13 | – | – | – | – |
| 120 | 2.530 | 95.78 | 1.242 | 95.15 | 0.812 | 94.51 | 0.377 | 92.38 | 0.314 | 91.60 | 0.264 | 90.68 |
| 140 | 2.623 | 98.85 | 1.291 | 98.26 | 0.846 | 97.65 | 0.397 | 95.65 | 0.332 | 94.96 | 0.282 | 94.12 |
| 160 | 2.716 | 101.97 | 1.340 | 101.42 | 0.880 | 100.84 | 0.417 | 98.96 | 0.350 | 98.34 | 0.298 | 97.57 |

having important influence on lubricant performance, are best evaluated by tests in the actual unit.

**Brines.** There are many refrigeration applications where direct-expansion evaporators, p 82, cannot be used, while there are others in which it is impossible to locate the evaporator in the area or substance to be cooled or frozen. Also, chilled water cannot be used below about 33 F. To serve such jobs brines are commonly used in *indirect* systems.

The usual hookup of an indirect system consists of a brine cooler, a brine pump and distributing piping. Cooler, usually of shell-and-tube design, acts as the evaporator for the refrigerant. Cold brine is circulated by the pump to the areas requiring cooling. Where compressor operating periods must be limited, hold-over or congealing tanks may be used for brine storage.

Commonly used brines are water solutions of calcium, sodium or magnesium chloride. Brine freezing point depends on solution strength, as tables, *right*, show. Calcium-chloride and sodium-chloride brines are the most widely used, with calcium chloride suitable for lower temperatures. Other brines include some of the glycols, alcohol and glycerin.

# Suggested lubricant viscosity ranges

| | Recommended viscosity ranges, ssu at 100 F |
|---|---|
| SMALL SYSTEMS (Rec-Reciprocating compressor, Rot-Rotary, Cen-Centrifugal) | |
| Rec: Carbon dioxide, methyl chloride, Freon-12, 21; Rot. Freon-114, sulfur dioxide; Cen: methylene chloride, Freon-11, 12, 113 | 280-300 |
| Rec: Ammonia; Rot: methylene chloride | 150-300 |
| Sulfur dioxide (Rec) | 70-200 |
| INDUSTRIAL REFRIGERATION (ammonia and carbon-dioxide compressors) | |
| Where oil may enter refrigeration system or compressor cylinders | 150-300 |
| Where oil is prevented from entering system or cylinders: (1) in force-feed or gravity systems | 500-600 |
| (2) in splash systems | 150-160 |
| Steam-driven compressor cylinders when condensate is reclaimed for ice making | 140-165 at 210 F |
| MISCELLANEOUS EQUIPMENT | |
| Bearings: (1) ring oiled, normal temperature | 280-300 |
| (2) ring oiled, low temperature | 100-115 |
| (3) chain oiled | 280-300 |
| Ball and roller bearings, oil lubricated | 280-300 |
| Wick oilers | 280-600 |

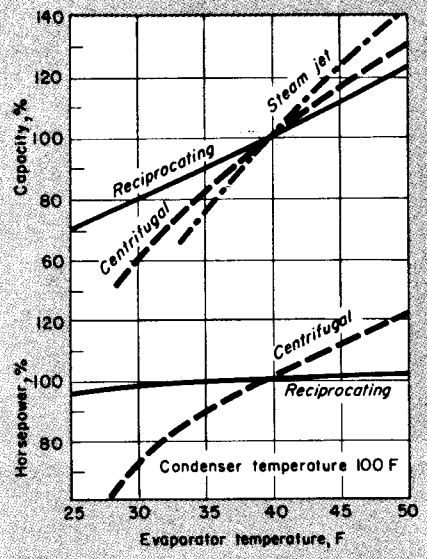
# Physical properties of brines

## Sodium chloride

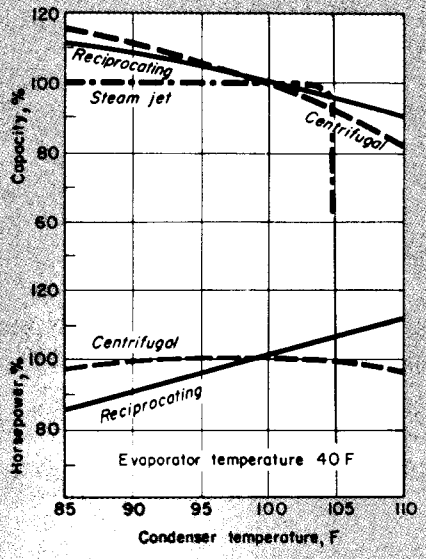
| % pure NaCl by weight | Specific gravity at 59 F | Specific heat at 59 F | Freezing point, F | Wt, lb per gal NaCl | Wt, lb per gal Water |
|---|---|---|---|---|---|
| 0 | 1.000 | 1.000 | 32.0 | 0.000 | 8.35 |
| 5 | 1.035 | 0.938 | 27.0 | 0.432 | 8.22 |
| 10 | 1.072 | 0.888 | 20.4 | 0.895 | 8.05 |
| 15 | 1.111 | 0.847 | 12.0 | 1.392 | 7.89 |
| 20 | 1.150 | 0.813 | 1.8 | 1.920 | 7.68 |
| 25 | 1.191 | 0.786 | 16.1 | 2.488 | 7.46 |

## Calcium chloride

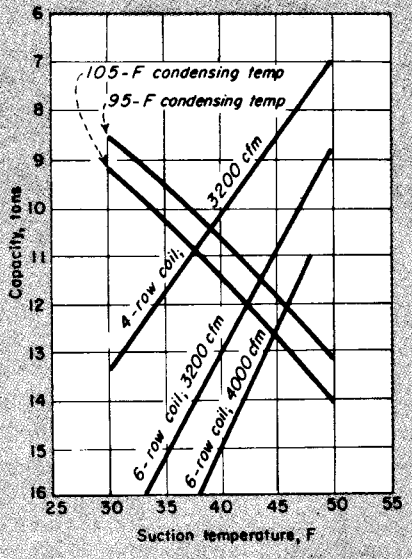
| % pure $CaCl_2$ by weight | Specific gravity at 60 F | Specific heat at 60 F | Freezing point, F | Wt, lb per gal $CaCl_2$ | Wt, lb per gal Water |
|---|---|---|---|---|---|
| 0 | 1.000 | 1.0000 | 32.0 | 0.000 | 8.350 |
| 5 | 1.044 | 0.9246 | 29.0 | 0.436 | 8.281 |
| 10 | 1.087 | 0.8556 | 23.0 | 0.908 | 8.168 |
| 15 | 1.133 | 0.7930 | 12.5 | 1.418 | 8.034 |
| 20 | 1.182 | 0.7375 | - 3.0 | 1.970 | 7.883 |
| 25 | 1.233 | 0.6899 | -25.0 | 2.574 | 7.721 |




**EVAPORATOR temperature and its effects on performance of various compressors***




**CONDENSER temperature and its effects on performance of various compressors***




**SYSTEM BALANCE can be studied on plot like this for compressor, evaporator**

## Refrigeration equipment for air-conditioning

Data from ASHAE "Guide," Chap. 37, 1955

| Capacity, tons | Majority used | Some used | Few used |
|---|---|---|---|
| 0 to 5 | Unit systems in conditioned space | Unit central systems, duct distribution | Built-up central systems |
| 5 to 25 | Built-up central systems, reciprocating compressors | Unit central systems, duct distribution | Unit systems in conditioned space<br>Built-up systems, absorption and adsorption systems |
| 25 to 50 | Built-up central systems, reciprocating compressors | Built-up central systems, centrifugal compressors | Central systems, adsorption systems |
| 50 to 400 | Built-up central systems, reciprocating compressors | Built-up central systems, steam-jet and centrifugal compressors | |
| 400 and over | Built-up central systems, centrifugal compressors | Built-up central systems, steam jet | |

## Compressor efficiency*

| Compression ratio | Volumetric efficiency, % | Performance factor, hp per ton |
|---|---|---|
| 2.0 | 88.50 | 0.72 |
| 2.2 | 87.00 | 0.81 |
| 2.4 | 85.60 | 0.89 |
| 2.6 | 84.20 | 0.96 |
| 2.8 | 82.90 | 1.05 |
| 3.0 | 81.60 | 1.13 |
| 3.2 | 80.03 | 1.20 |
| 3.4 | 79.10 | 1.27 |
| 3.6 | 78.00 | 1.34 |
| 3.8 | 76.70 | 1.41 |
| 4.0 | 75.60 | 1.47 |
| 4.2 | 74.50 | 1.54 |
| 4.4 | 73.50 | 1.60 |
| 4.6 | 72.50 | 1.67 |
| 4.8 | 71.40 | 1.73 |
| 5.0 | 70.04 | 1.78 |
| 5.2 | 68.90 | 1.84 |
| 5.4 | 68.40 | 1.90 |
| 5.6 | 67.40 | 1.96 |
| 5.8 | 66.40 | 2.02 |
| 6.0 | 65.30 | 2.07 |
| 6.2 | 64.30 | 2.13 |
| 6.4 | 63.40 | 2.18 |
| 6.6 | 62.50 | 2.24 |

* Approximate values for high-speed Freon units

# Equipment selection and use

Correct sizing of refrigeration equipment for a given load is extremely important—undersizing can lead to damage of expensive products or personnel discomfort, while oversizing may cause uneconomical operation. The aim of correct choice is a balanced system giving economical operation for all normal loads, with sufficient reserve for expected overloads.

First step in equipment selection is determination of heat loads expected. Heat may be gained from any one or all of four sources—the room or area refrigerated, the air in the room, stored products and miscellaneous sources.

Heat gain from the room results from transmission through the walls, ceiling and floor. Amount of heat gained depends on type of wall and floor construction, type and thickness of insulation, area insulated, and temperature difference between the inside and outside of the room.

Air enters a refrigerated space every time a door is opened. To maintain the desired temperature level within refrigerated room, temperature of the entering air must be reduced. This imposes a definite load on the equipment.

Products placed in the refrigerated area generally must have their temperature reduced, and in many instances must be frozen, requiring removal of additional energy in the form of heat, p 76. Amount of heat that must be re-

# Freon reciprocating compressor rating table

| Suction | | Condensing temperature and pressure | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 85 F | | 95 F | | 105 F | | 115 F | |
| Temp, F | Gage pressure, psi | 91.7 psi gage | | 108.1 psi gage | | 126.2 psi gage | | 146.3 psi gage | |
| | | Tons | BHP | Tons | BHP | Tons | BHP | Tons | BHP |
| −10 | 4.5 | 3.4 | 6.6 | 3.1 | 6.7 | 2.7 | 6.7 | 2.4 | 6.5 |
| −5 | 6.7 | 4.0 | 7.0 | 3.6 | 7.2 | 3.2 | 7.2 | 2.9 | 7.1 |
| 0 | 9.2 | 4.6 | 7.5 | 4.2 | 7.7 | 3.8 | 7.8 | 3.4 | 7.8 |
| 5 | 11.8 | 5.3 | 7.8 | 4.9 | 8.1 | 4.4 | 8.3 | 4.0 | 8.3 |
| 10 | 14.7 | 6.1 | 8.1 | 5.6 | 8.5 | 5.1 | 8.8 | 4.6 | 8.9 |
| 15 | 17.7 | 6.9 | 8.5 | 6.3 | 8.9 | 5.8 | 9.2 | 5.3 | 9.4 |
| 20 | 21.1 | 7.8 | 8.7 | 7.2 | 9.2 | 6.6 | 9.6 | 6.1 | 9.9 |
| 25 | 24.6 | 8.8 | 9.0 | 8.1 | 9.5 | 7.5 | 10.0 | 6.9 | 10.4 |
| 30 | 28.5 | 9.8 | 9.1 | 9.2 | 9.8 | 8.5 | 10.4 | 7.8 | 10.8 |
| 35 | 32.6 | 11.0 | 9.2 | 10.2 | 10.0 | 9.5 | 10.7 | 8.8 | 11.2 |
| 40 | 37.0 | 12.3 | 9.2 | 11.4 | 10.2 | 10.7 | 11.1 | 9.8 | 11.5 |
| 45 | 41.7 | 13.6 | 9.1 | 12.7 | 10.2 | 11.9 | 11.2 | 11.0 | 11.9 |

# Rating table for absorption refrigeration machines

| | Internal-coil machines | | | | | | | | | | | Open machines | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Nominal capacity, tons** (45-F chilled water, 85-F condensing water, 12-psig steam) | 103 | 137 | 182 | 232 | 260 | 300 | 334 | 424 | 485 | 585 | 691 | 109 | 145 | 193 | 245 | 275 | 317 | 353 | 448 | 512 | 619 | 731 |
| **Nominal steam rate**, lb per hr per ton | 19.6 | 19.6 | 19.6 | 19.6 | 19.6 | 19.6 | 19.6 | 19.6 | 19.6 | 19.6 | 19.6 | 19.0 | 19.0 | 19.0 | 19.0 | 19.0 | 19.0 | 19.0 | 19.0 | 19.0 | 19.0 | 19.0 |
| Solution | 1½ | 1½ | 2 | 5 | 5 | 5 | 5 | 7½ | 7½ | 7½ | 7½ | 1½ | 1½ | 2 | 5 | 5 | 5 | 5 | 7½ | 7½ | 7½ | 7½ |
| **Pump horsepowers**—Evaporator | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 5 | 5 | 5 | 5 | – | – | – | – | – | – | – | – | – | – | – |
| Purge | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 4 | 4 | 4 | 4 |
| **Condensing water, gpm** | 400 | 525 | 700 | 850 | 945 | 1100 | 1225 | 1560 | 1750 | 2150 | 2450 | 400 | 525 | 700 | 850 | 945 | 1100 | 1225 | 1560 | 1750 | 2150 | 2450 |
| **Condensing-water pressure drop** (total, ps | 14 | 19 | 12 | 13 | 15 | 14 | 16 | 15 | 18 | 10 | 14 | 14 | 19 | 12 | 13 | 15 | 14 | 16 | 15 | 18 | 10 | 14 |
| **Absorber passes** | 4 | 3 | 2 | 3 | 3 | 2 | 2 | 3 | 3 | 2 | 2 | 4 | 3 | 2 | 3 | 3 | 2 | 2 | 3 | 3 | 2 | 2 |
| **Chilled water, gpm** | – | – | – | – | – | – | – | – | – | – | – | 275 | 360 | 480 | 610 | 685 | 790 | 875 | 1110 | 1270 | 1530 | 1820 |
| **Condensate** (max. startup) lb per hr for steam trap selection only | 7,500 | 10,200 | 13,800 | 17,100 | 19,500 | 22,200 | 25,200 | 31,200 | 36,300 | 43,800 | 54,000 | 7,500 | 10,200 | 13,800 | 17,100 | 19,500 | 22,200 | 25,200 | 31,200 | 36,300 | 43,800 | 54,000 |

# Typical rating chart for centrifugal compressors

| Pass arrangement and gpm range | Leaving chilled-water temp, F | Leaving condenser-water temperature: 80 F | | | 85 F | | | 90 F | | | 95 F | | | 100 F | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | A | B | C | A | B | C | A | B | C | A | B | C | A | B | C |
| 4-pass evaporator | 40 | | | 178.7 | | | 174.4 | | | 169.2 | | | 160.1* | | | 147.6* |
| 143-470 gpm | 42 | | | 182.0 | | | 178.3 | | | 173.5 | | | 167.8 | | | 156.8* |
| velocity, fps = gpm × .021 | 44 | | 192.6 | 185.3 | | 188.4 | 181.5 | | 183.3 | 177.2 | | | 171.8 | | | 165.5 |
| | 46 | | 196.3 | | | 192.1 | | | 187.2 | 180.0 | | 181.0 | 175.2 | | | 169.3 |
| 4-pass condenser | 48 | 206.6 | 200.0 | | 200.9 | 195.7 | | 190.5* | 191.2 | | | 185.3 | 177.8 | | 178.3 | 172.3 |
| 120-404 gpm | 50 | 212.2 | | | 207.7 | | | 202.5 | 194.9 | | 195.0 | 189.6 | | | 183.2 | |
| velocity, fps = gpm × .025 | 52 | 216.6 | | | 212.3 | | | 207.4 | | | 201.0 | 193.0 | | 192.9 | 186.5 | |
| 4-pass evaporator | 40 | | | 177.5 | | | 173.1 | | | 168.0 | | | 156.4* | | | |
| 143-470 gpm | 42 | | | 181.1 | | | 177.3 | | | 172.0 | | | 166.0 | | | 152.2* |
| velocity, fps = gpm × .021 | 44 | | 191.7 | 184.2 | | 187.1 | 180.2 | | 181.6 | 175.8 | | 167.5* | 170.3 | | | 163.9 |
| | 46 | | 195.2 | | | 190.7 | | | 185.7 | | | 178.7 | 173.9 | | | 167.8 |
| 3-pass condenser | 48 | 205.7 | 198.6 | | 196.5* | 194.4 | | | 189.7 | | | 183.8 | 176.5 | | 176.1 | 170.8 |
| 158-539 gpm | 50 | 210.7 | | | 206.5 | | | 200.3 | 193.5 | | 189.0* | 187.7 | | | 181.3 | 173.0 |
| velocity, fps = gpm ÷ .019 | 52 | 215.5 | | | 210.8 | | | 205.8 | | | 198.5 | 191.4 | | | 184.7 | |

Boldface numbers indicate rated capacities, tonnage; italicized numbers are for reference or interpolation. Capacities based on 165 bhp using Freon-113. A, B and C indicate different impeller combinations.
*These ratings require less than 165 bhp

# Tonnage capacity of Freon piping

| | | Outside diameter of pipe, in. | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Length of pipe, ft | Pressure drop, psi | 5/8 | 7/8 | 1 1/8 | 1 3/8 | 1 5/8 | 2 1/8 | 2 5/8 | 3 1/8 | 3 5/8 | 4 1/8 | 5 1/8 | 6 1/8 |
| | | Inside diameter of pipe, in. | | | | | | | | | | | |
| | | 0.545 | 0.785 | 1.025 | 1.265 | 1.505 | 1.985 | 2.465 | 2.945 | 3.425 | 3.905 | 4.875 | 5.845 |
| **Compressor discharge lines** | | | | | | | | | | | | | |
| | 1 | 0.6 | 1.6 | 3.2 | 5.7 | 9.1 | 19.0 | 34.1 | 55 | 82 | 117 | 213 | 347 |
| | 2 | 0.9 | 2.3 | 4.8 | 8.4 | 13.4 | 28.2 | 50.5 | 82 | 122 | 173 | 315 | 512 |
| 50 | 3 | 1.1 | 2.9 | 6.0 | 10.5 | 16.8 | 35.4 | 63.2 | 102 | 153 | 218 | 395 | 643 |
| | 4 | 1.3 | 3.5 | 7.1 | 12.4 | 19.7 | 41.6 | 74.5 | 120 | 180 | 256 | 465 | 757 |
| | 5 | 1.4 | 3.9 | 8.0 | 14.1 | 22.4 | 47.1 | 84.4 | 136 | 204 | 291 | 526 | 857 |
| **Compressor suction lines** | | | | | | | | | | | | | |
| | 1 | 0.4 | 1.1 | 2.2 | 3.8 | 6.1 | 12.8 | 23.0 | 37 | 55 | 79 | 144 | 234 |
| | 2 | 0.6 | 1.6 | 3.2 | 5.7 | 9.1 | 19.0 | 34.1 | 55 | 82 | 117 | 213 | 347 |
| 50 | 3 | 0.8 | 2.0 | 4.1 | 7.1 | 11.4 | 24.1 | 43.0 | 70 | 104 | 148 | 269 | 437 |
| | 4 | 0.9 | 2.4 | 4.8 | 8.4 | 13.5 | 28.3 | 50.7 | 82 | 122 | 174 | 316 | 515 |
| | 5 | 1.0 | 2.6 | 5.4 | 9.6 | 15.4 | 32.3 | 57.7 | 94 | 139 | 199 | 360 | 587 |
| **Liquid lines** | | | | | | | | | | | | | |
| | 1 | 2.8 | 7.6 | 15.5 | 27.3 | 43.4 | 91.0 | 103.2 | 264 | 395 | 562 | | |
| | 2 | 4.2 | 11.1 | 22.9 | 40.2 | 64.1 | 135.2 | 241.4 | 389 | 583 | 830 | | |
| 50 | 3 | 5.3 | 14.0 | 28.7 | 50.5 | 80.5 | 169.2 | 302.6 | 489 | 733 | 1042 | | |
| | 4 | 6.2 | 16.5 | 33.7 | 59.4 | 94.4 | 198.9 | 356.2 | 575 | 861 | 1225 | | |
| | 5 | 7.1 | 18.7 | 38.3 | 67.3 | 107.1 | 225.3 | 403.8 | 651 | 976 | 1389 | | |

Note: Recommended pressure drop at maximum load shown in boldface type

moved is a function of the total weight of product placed in the refrigerated area, its temperature, specific heat, final temperature desired, and the number of Btu that must be given up to produce freezing, if the product is to be frozen. On some jobs this last quantity represents a major portion of the product load.

Miscellaneous heat loads include those from electrical devices within the refrigerated space—lights, motors, etc—people within the space, piping and any other sources. To secure accurate results, these must be carefully evaluated. Note that the four heat sources given above apply equally well to any job.

Second step is choice of compressor type. Table, p 92, shows typical units chosen for air-conditioning jobs. Text, pp 88-89, gives details on the usual types of units chosen for various other classes of jobs—industrial, ice-making, etc. Tables, p 93, show typical rating details that must be reviewed when choosing reciprocating, centrifugal and absorption units. Efficiencies of typical reciprocating units are also shown.

With compressor type and capacity known, the remaining components of the system must be chosen. These include the condenser, evaporator, expansion valve, controls and piping. Earlier pages in this report cover these items.

Piping deserves particular attention during system planning because use of the wrong sizes or types can seriously handicap an otherwise good job. Table, p 93, shows sizes for various tonnages on Freon jobs.

Whenever in doubt about the proper type or size of compressor, component or system to be used, secure the aid of equipment manufacturers and a consulting engineer. Correct choice is too important to be given only passing study.

# Equipment use

Factors important in equipment use include head and suction pressures, condenser-water supply, expansion-valve setting, compressor lubrication and load on the machine. While conditions vary from one job to the next, here are some pointers to watch with each compressor type:

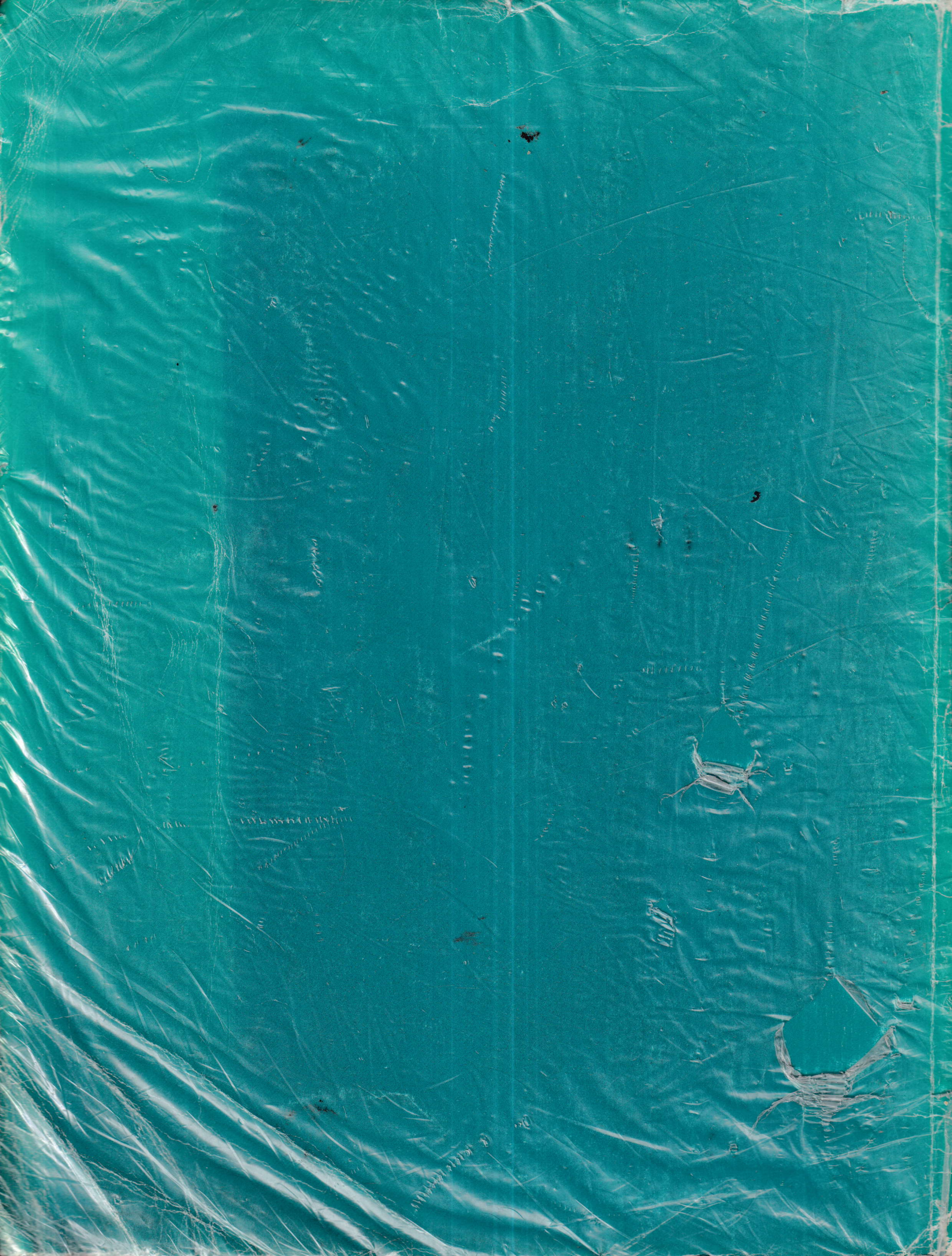
**Reciprocating.** Keep head pressure within recommended limits at all times. Automatic purge units are useful. Excessive head pressure means high side has air and other noncondensable gases trapped in it, increasing the required power input and reducing system capacity. Purge high side to remove air and gas.

Don't pull suction pressure too low—liquid refrigerant may reach compressor suction, where it can do damage. Watch suction-line frost; it's a fair indicator of whether the pressure is right. Keep an eye on your compressor gages and controls at all times—they show up troubles in the making.

Get advice before making final choice of compressor lubricating oil. The right oil goes a long way toward making compressor operation more dependable, and can aid in increasing system operating economy. So don't guess; it doesn't pay.

**Centrifugal.** Usually fitted with built-in purge units, head pressure in these machines is less likely to give trouble than with reciprocating compressors. On most jobs it is common practice to run the purge unit before the main machine is started to insure ridding the machine of noncondensables.

Surging in many centrifugals is normal, and there's nothing to worry about except at low loads. At 10 to 20% of full load, surging can cause compressor to overheat, raising bearing temperature. So don't operate continuously under these conditions without getting advice from the manufacturer.

**Absorption, steam-jet.** With both these types, steam supply is extremely important because without it no refrigerating effect can be produced. So be sure you always have enough steam at pressure the unit requires.

POWER wishes to thank the many refrigeration-equipment manufacturers who offered advice and criticism during preparation of this report.